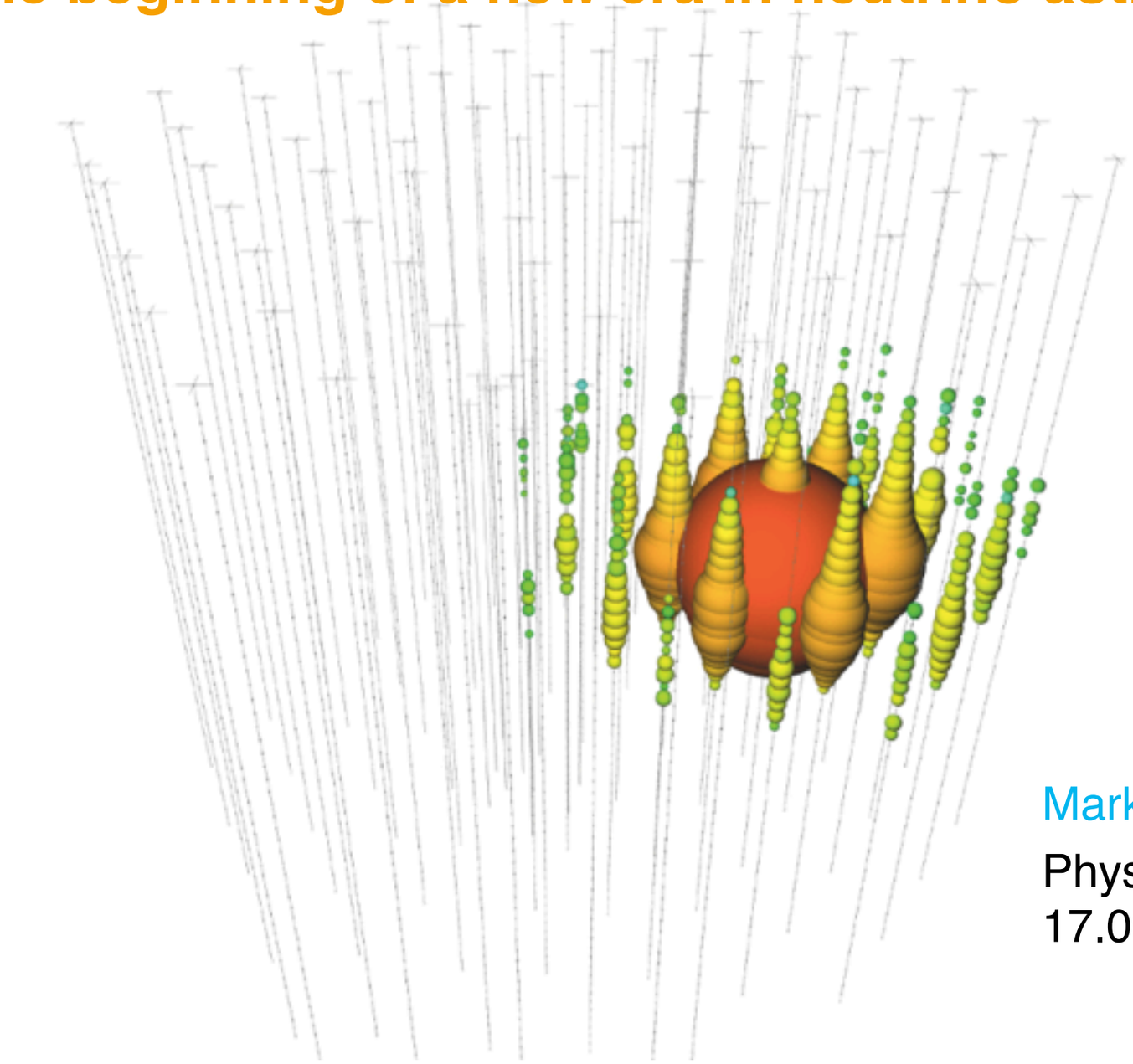
IceCube

the beginning of a new era in neutrino astrophysics.



Markus Ackermann

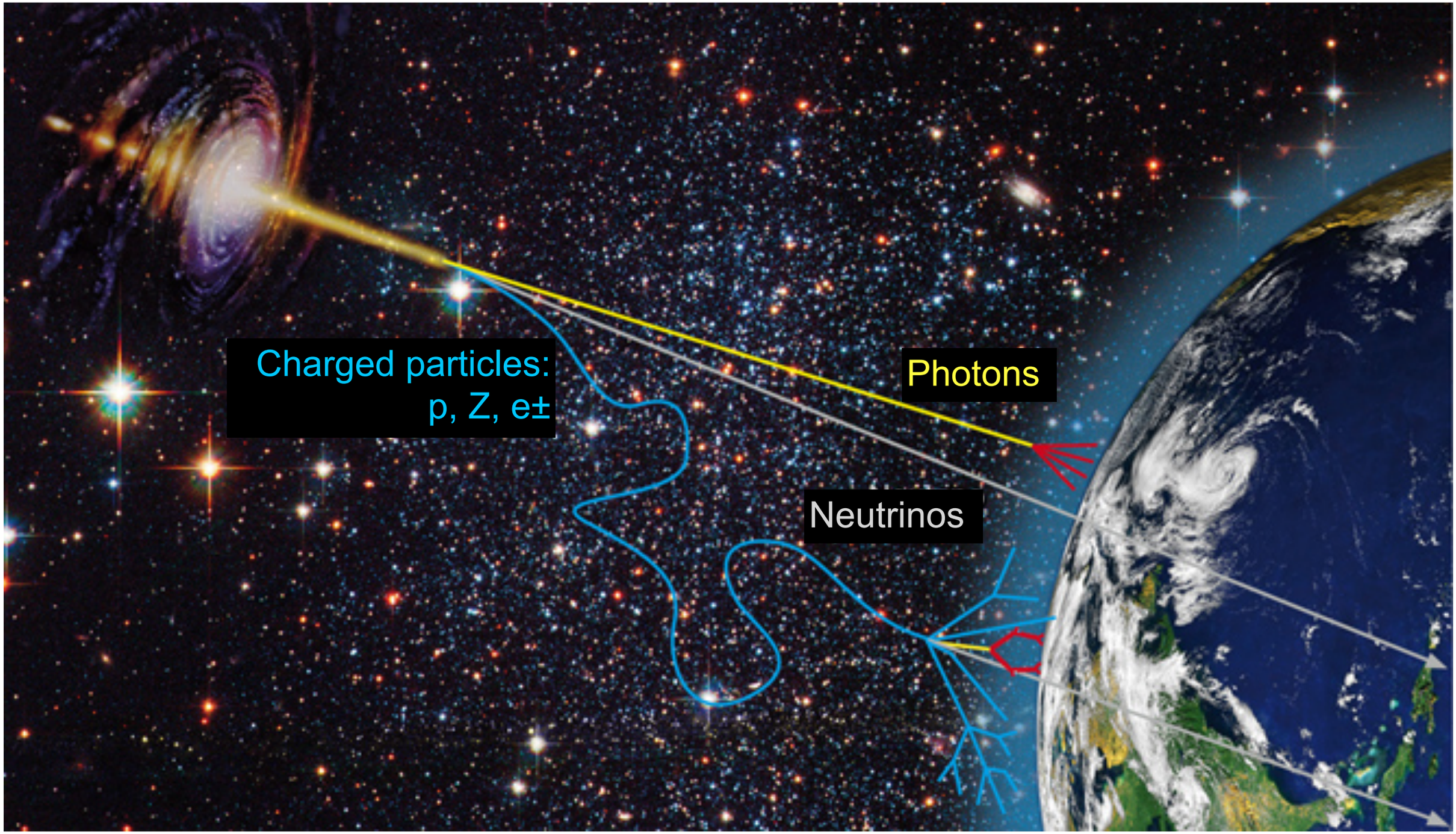
Physik-Seminar, DESY
17.09.2013 (Hamburg) / 25.09.2013 (Zeuthen)

HELMHOLTZ ASSOCIATION

DESY

High-energy astrophysics

> Three messengers are available to study the non-thermal universe.



The power of neutrino observations.

> Neutrinos are a diagnostic of **hadronic acceleration sites and processes.**

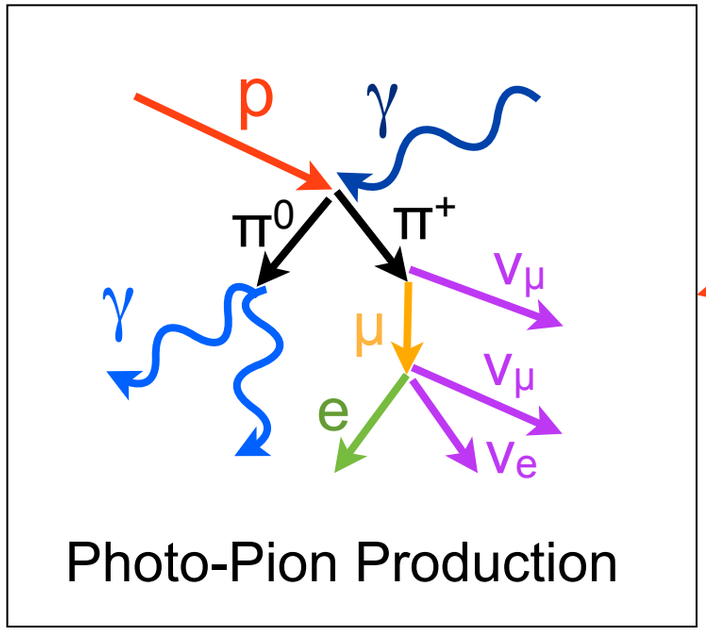
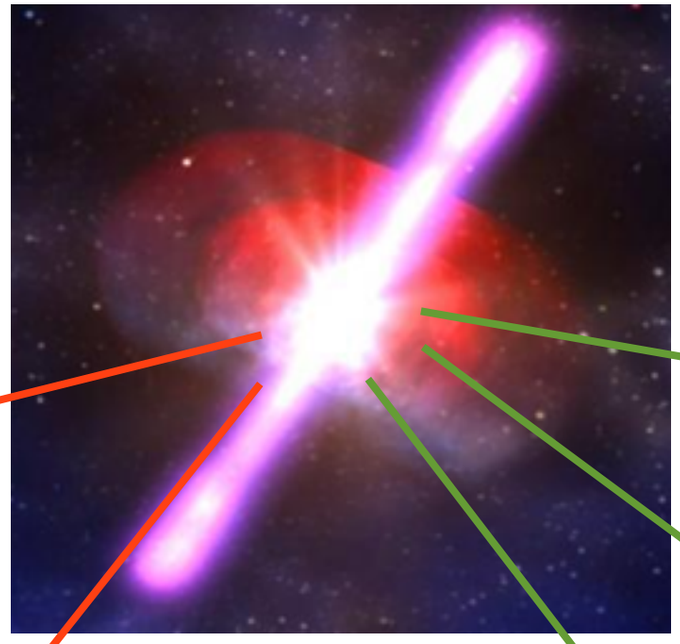
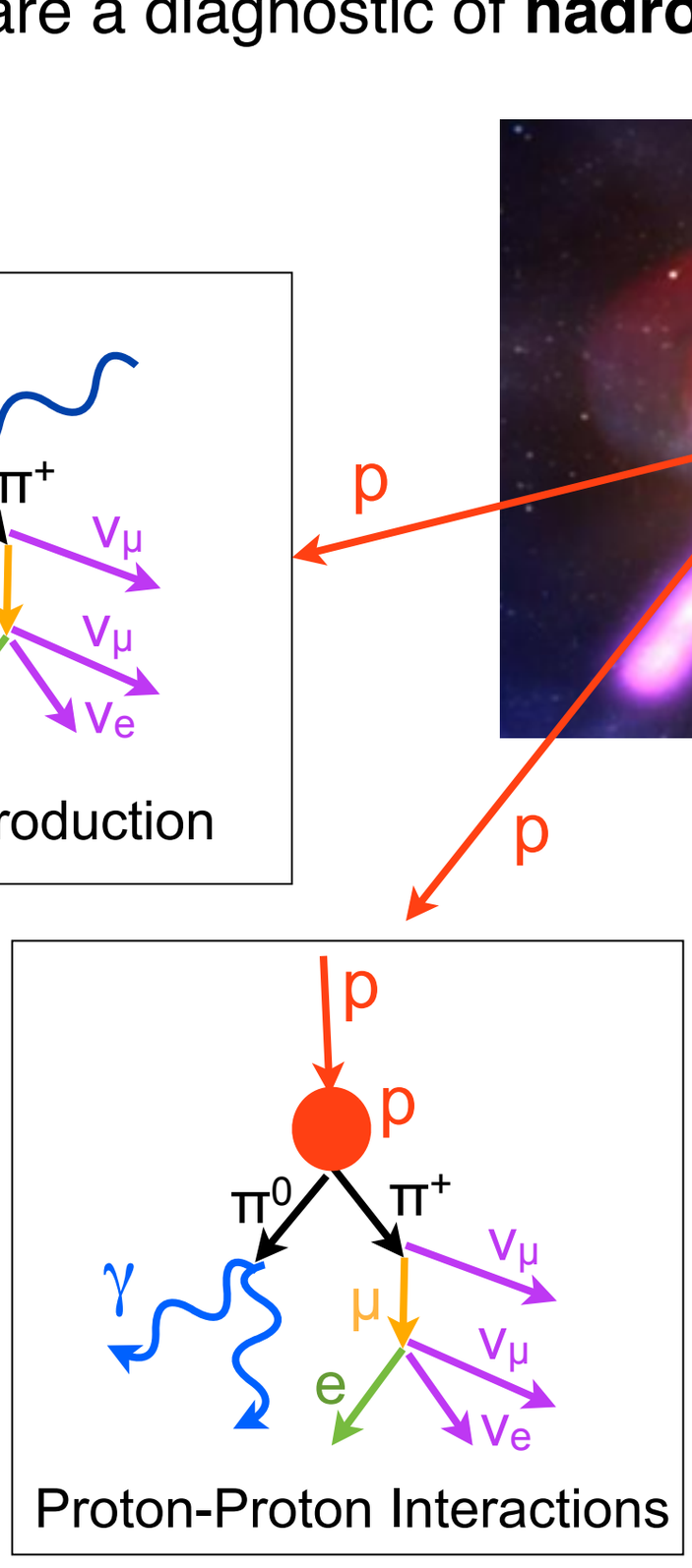
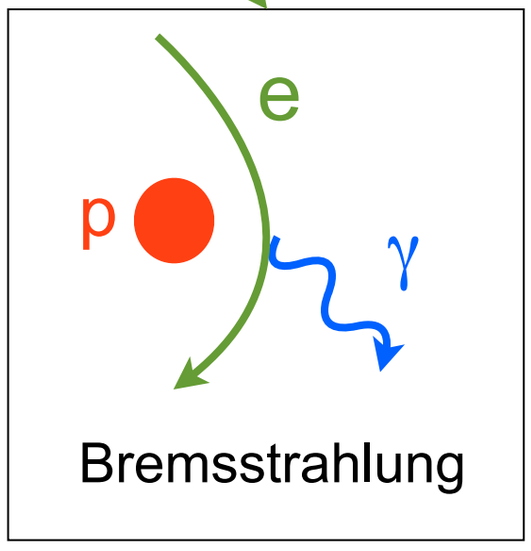


Photo-Pion Production

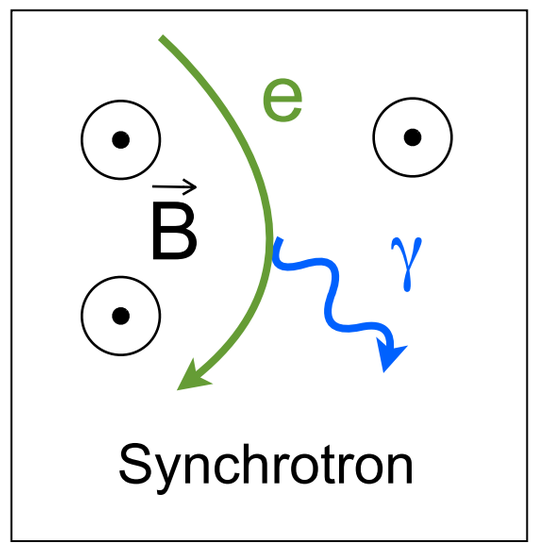




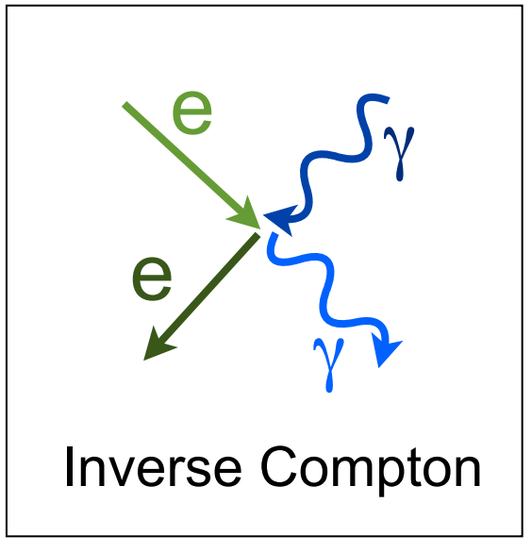
Proton-Proton Interactions



Bremsstrahlung



Synchrotron



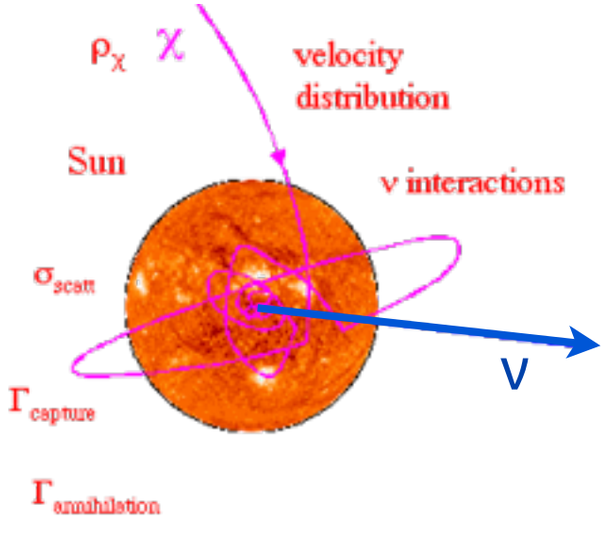
Inverse Compton

The power of neutrino observations.

Neutrinos can **escape dense environments:**

> High-energy neutrinos from core-collapse SNe.
(e.g. Ando & Beacom, 2005)

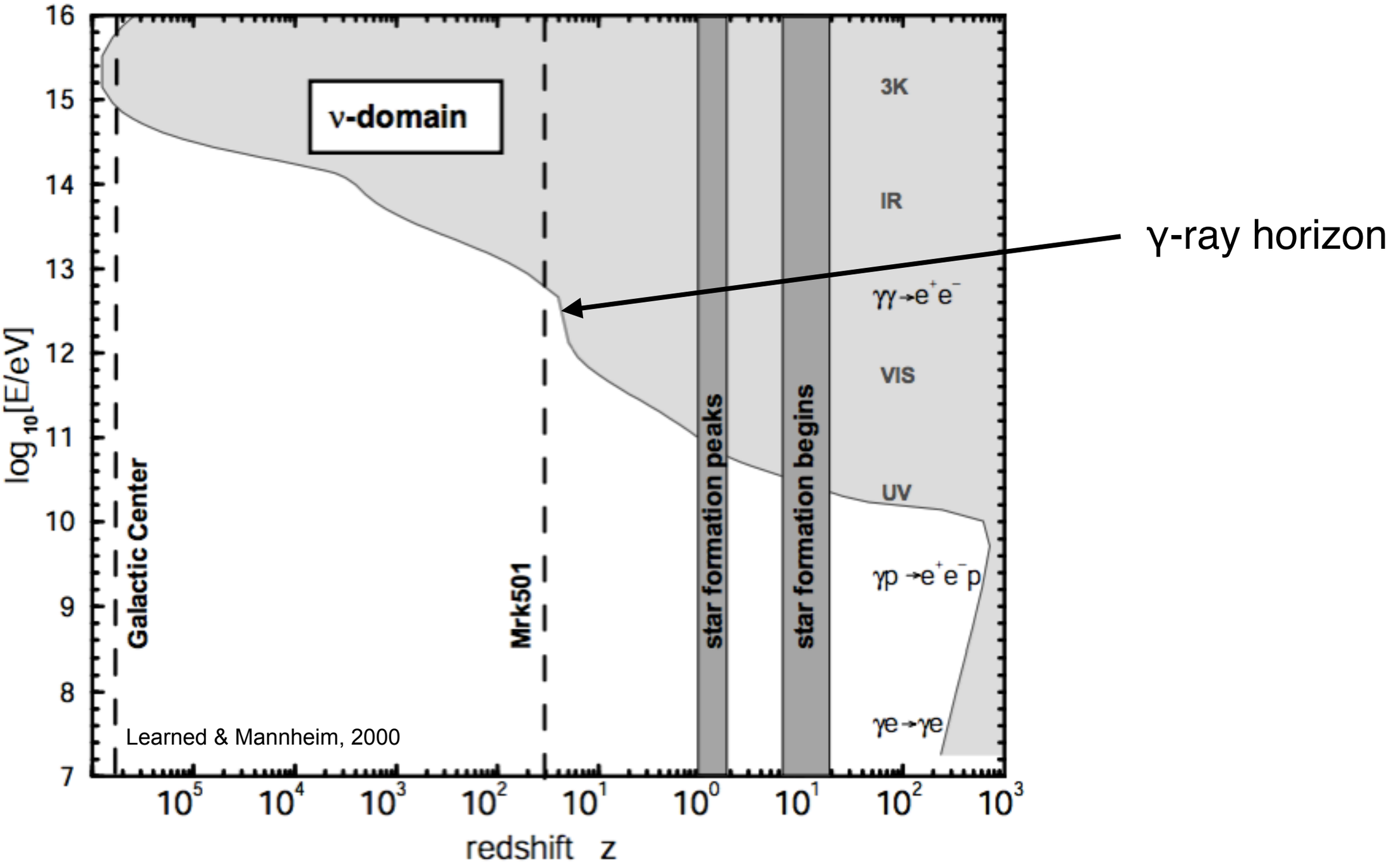
> Neutrinos from the cores of active galactic nuclei
(e.g. Stecker et al., 1991)



> High-energy neutrinos from dark matter annihilation in the sun.

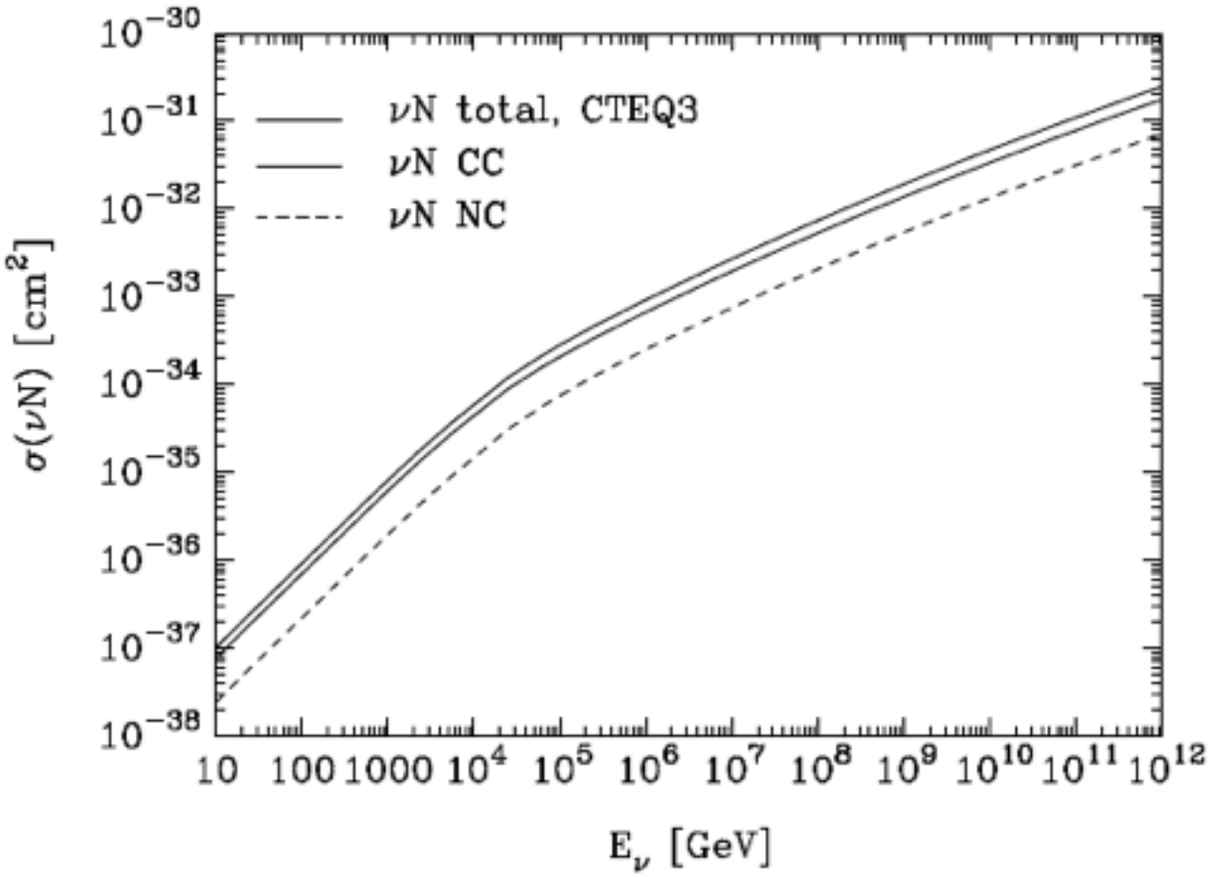
The neutrino domain: PeV astronomy.

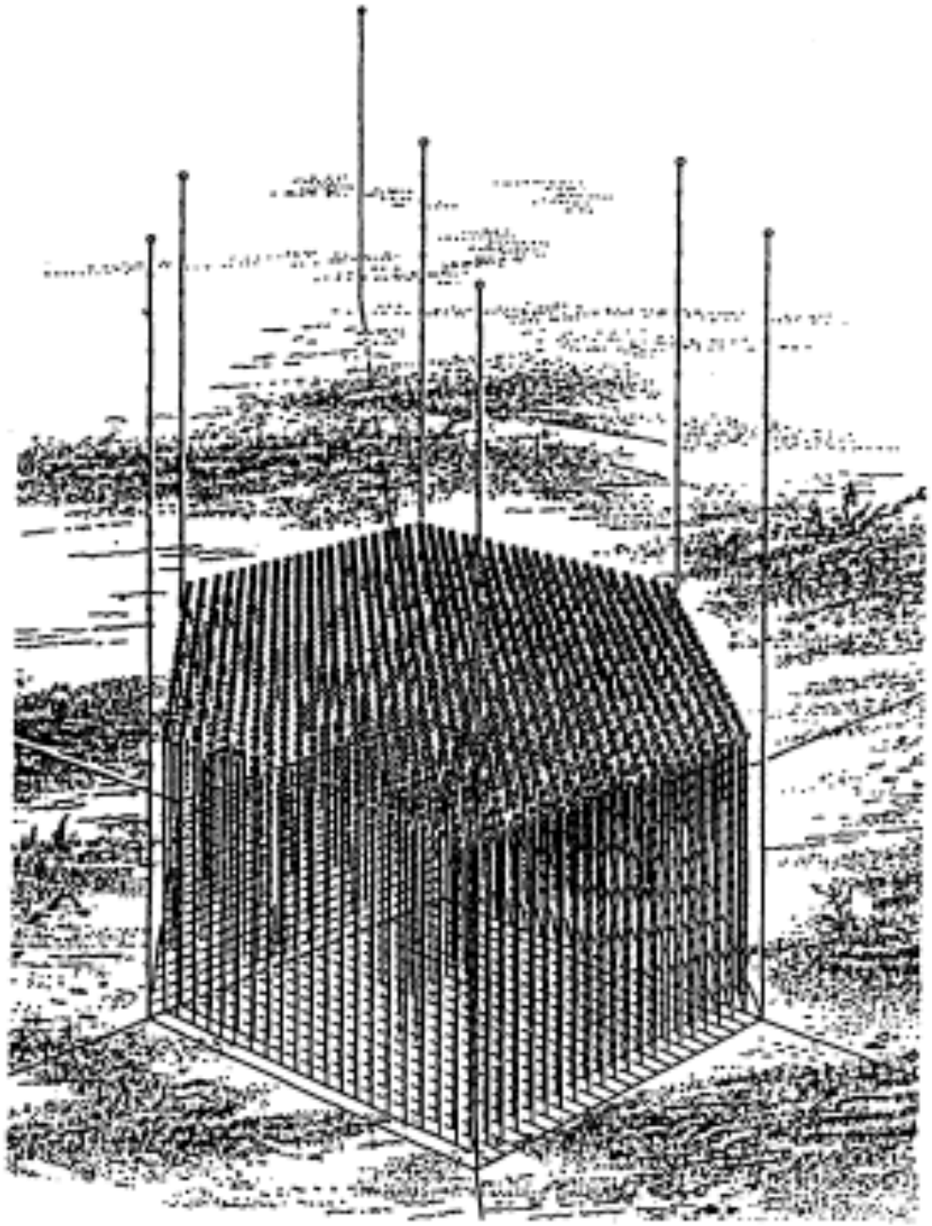
- Above 100 GeV the **universe** starts to turn **opaque for γ-rays**.
- Only neutrino telescopes can do **PeV/EeV astronomy.**



Neutrino astrophysics.

> **Small cross-section** of neutrinos requires **huge detectors.**



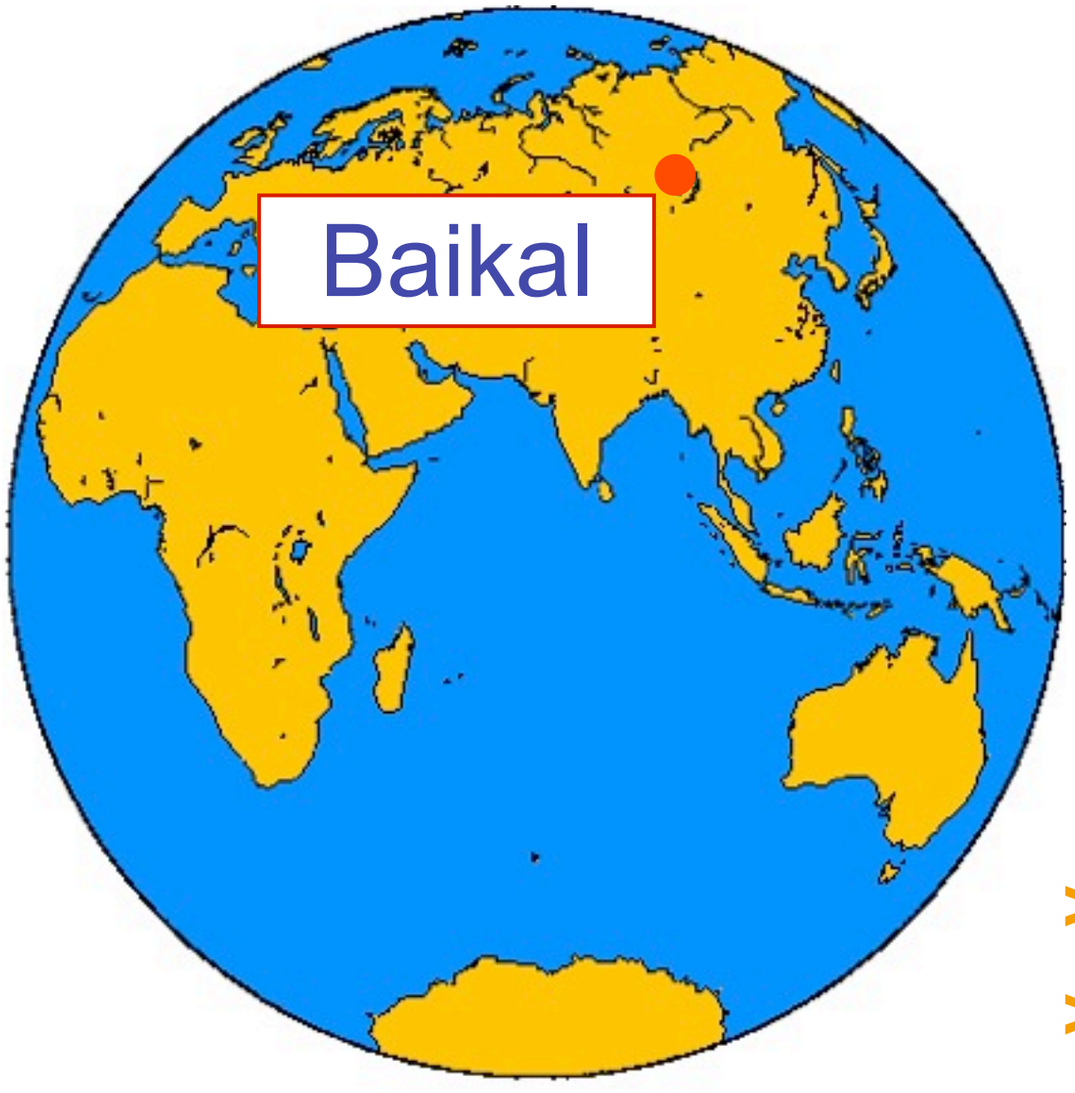


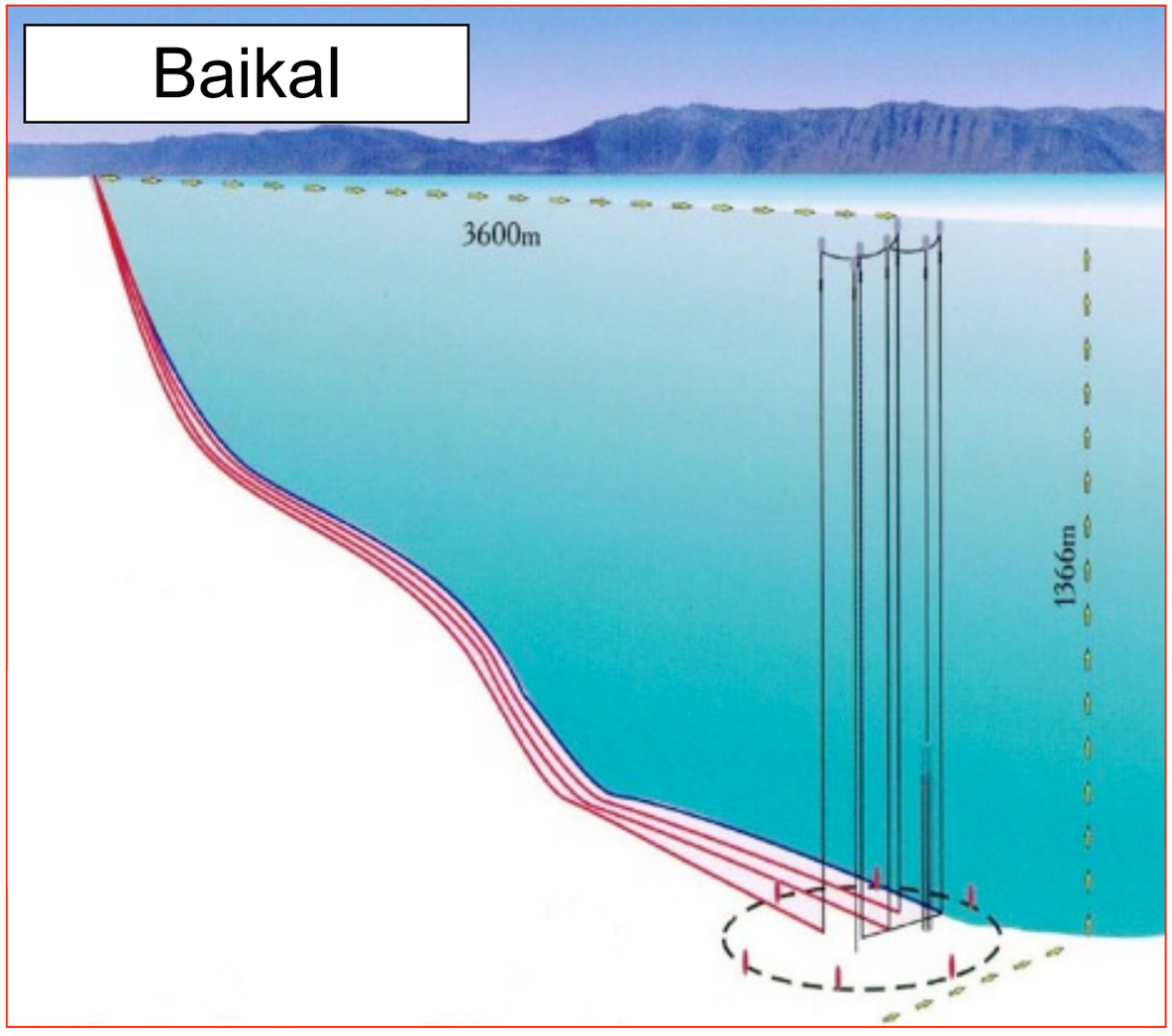
> **First design** of a **1 km^3** underwater detector already in 1978

- DUMAND array off the coast of Hawaii
- Never built after first test strings failed

> **35 years later** we are finally there....

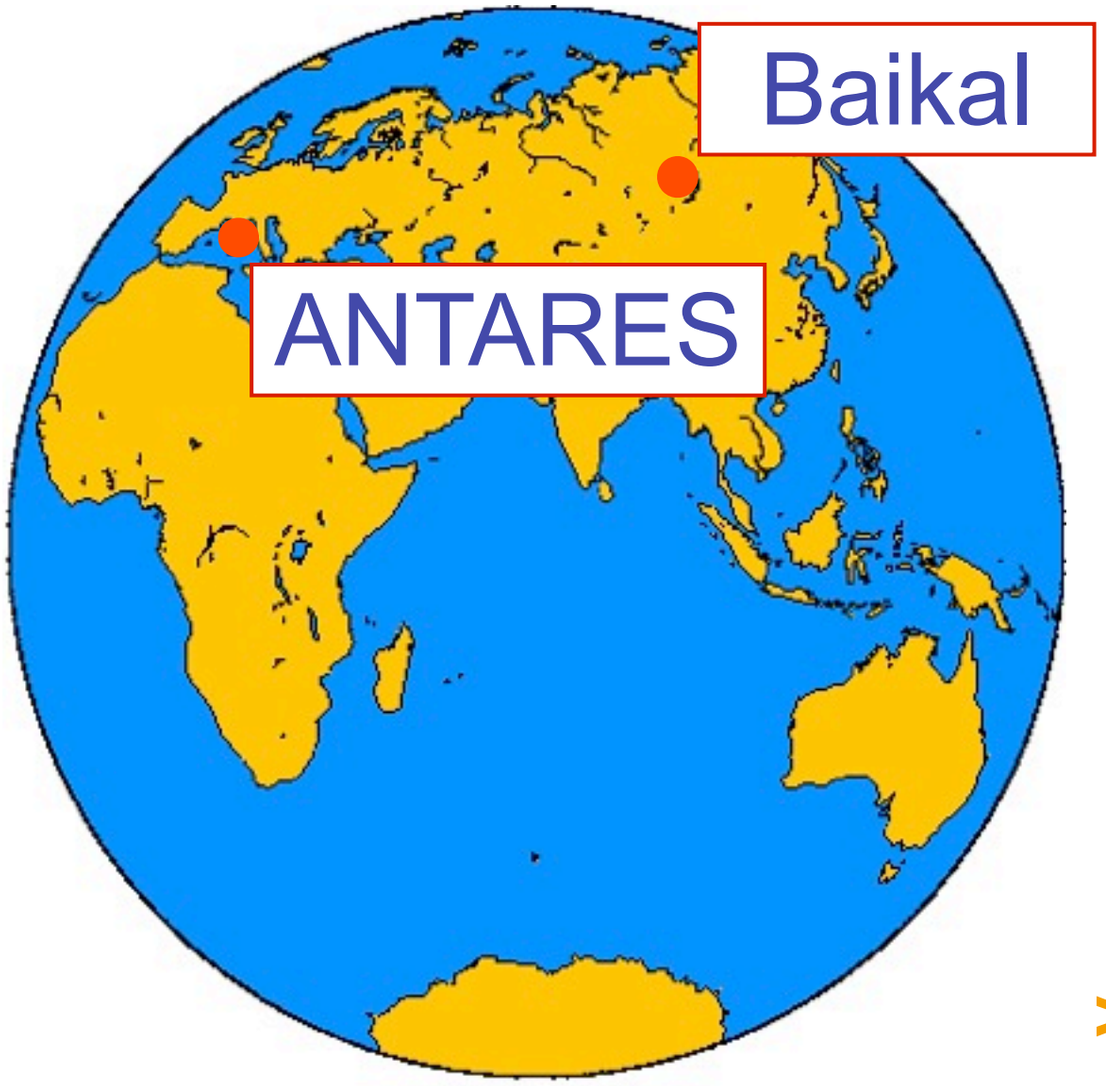
Operating neutrino telescopes: Baikal

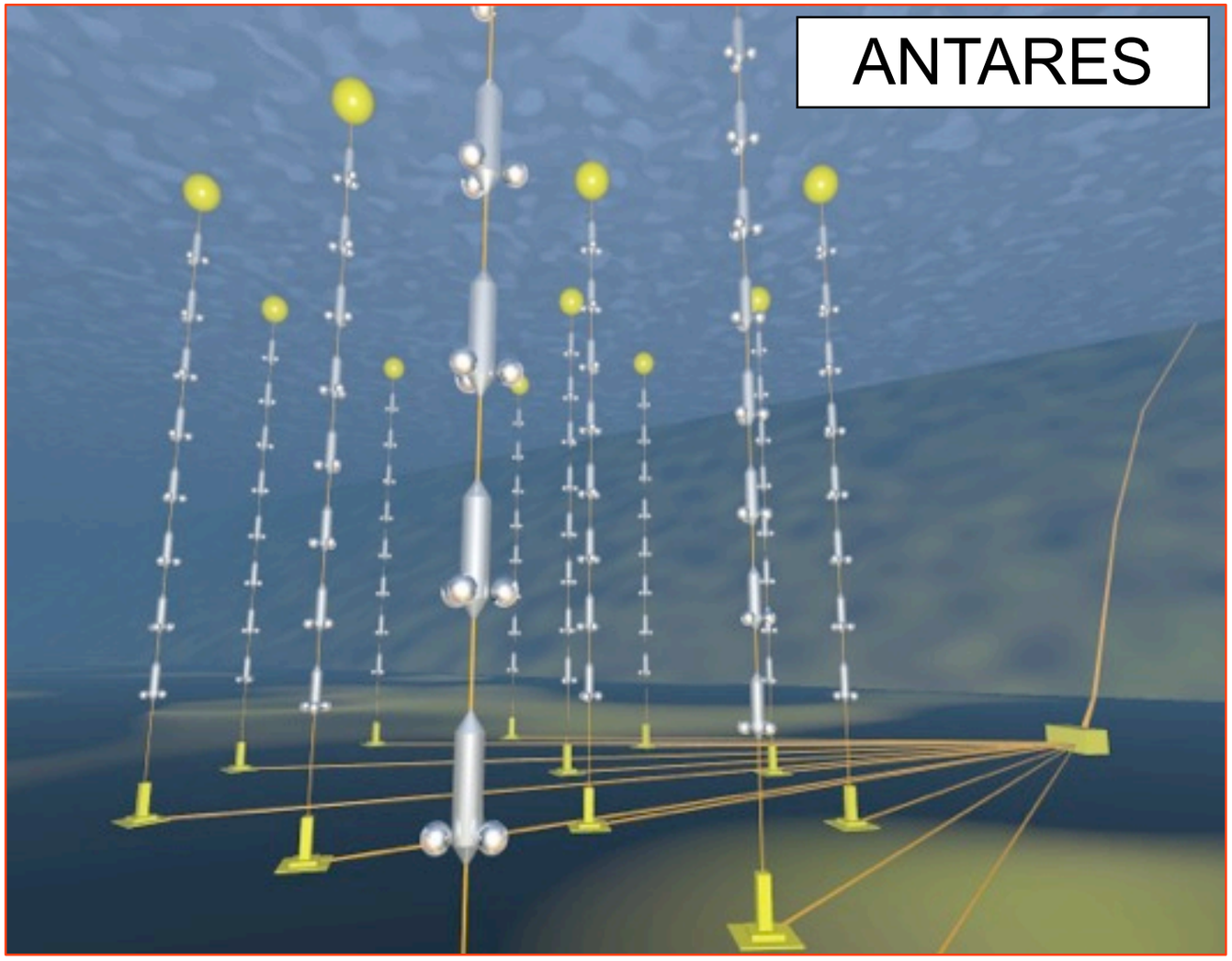




- ~ 4km off the shore of **Lake Baikal**
- **Completed** in **1998**
- 192 optical sensors on 8 strings
  (**10^{-4} km³** instrumented volume)
- Upgraded to NT200+ configuration in 2007
  (+18 sensors on 3 strings)

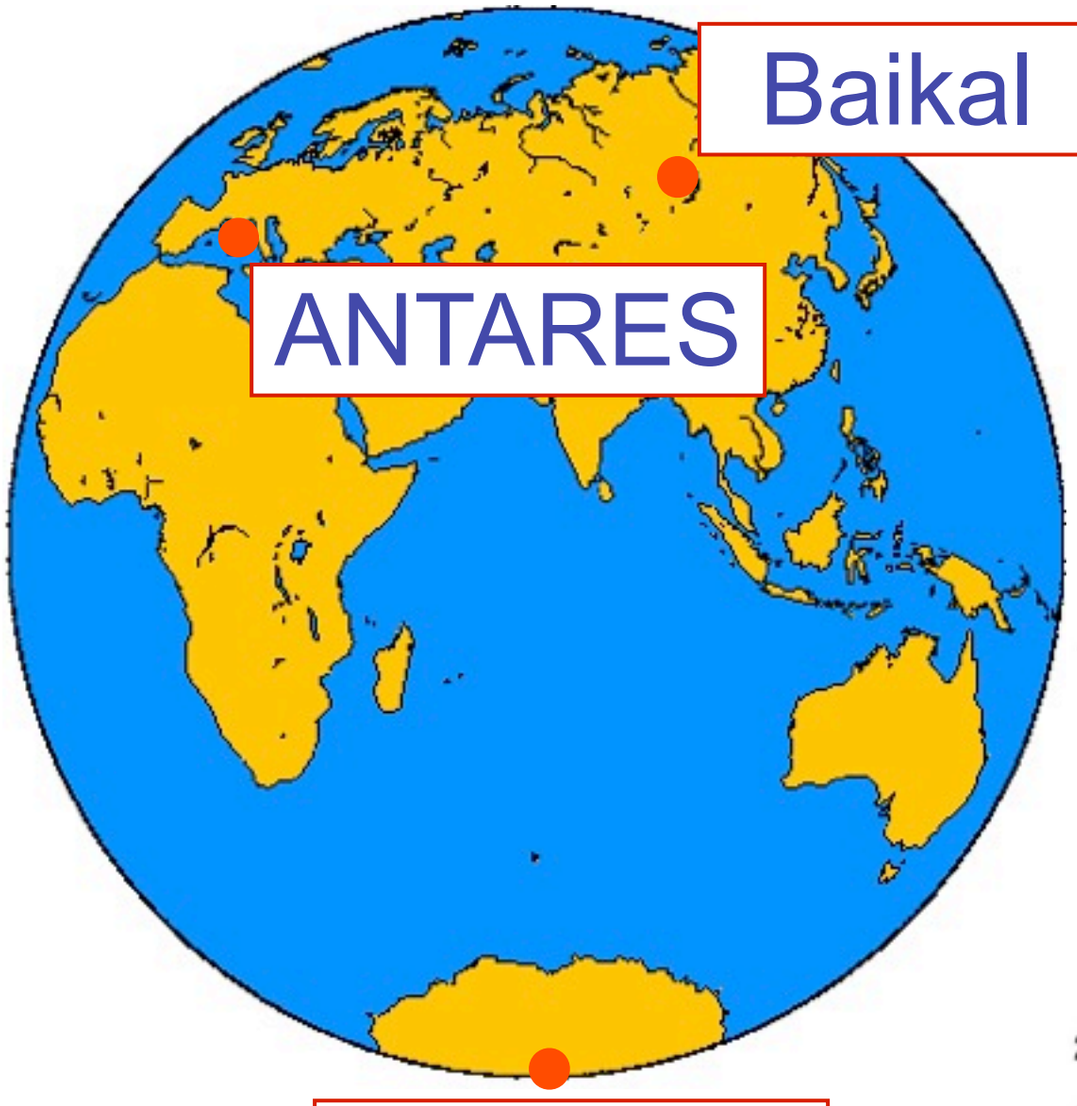
Operating neutrino telescopes: ANTARES

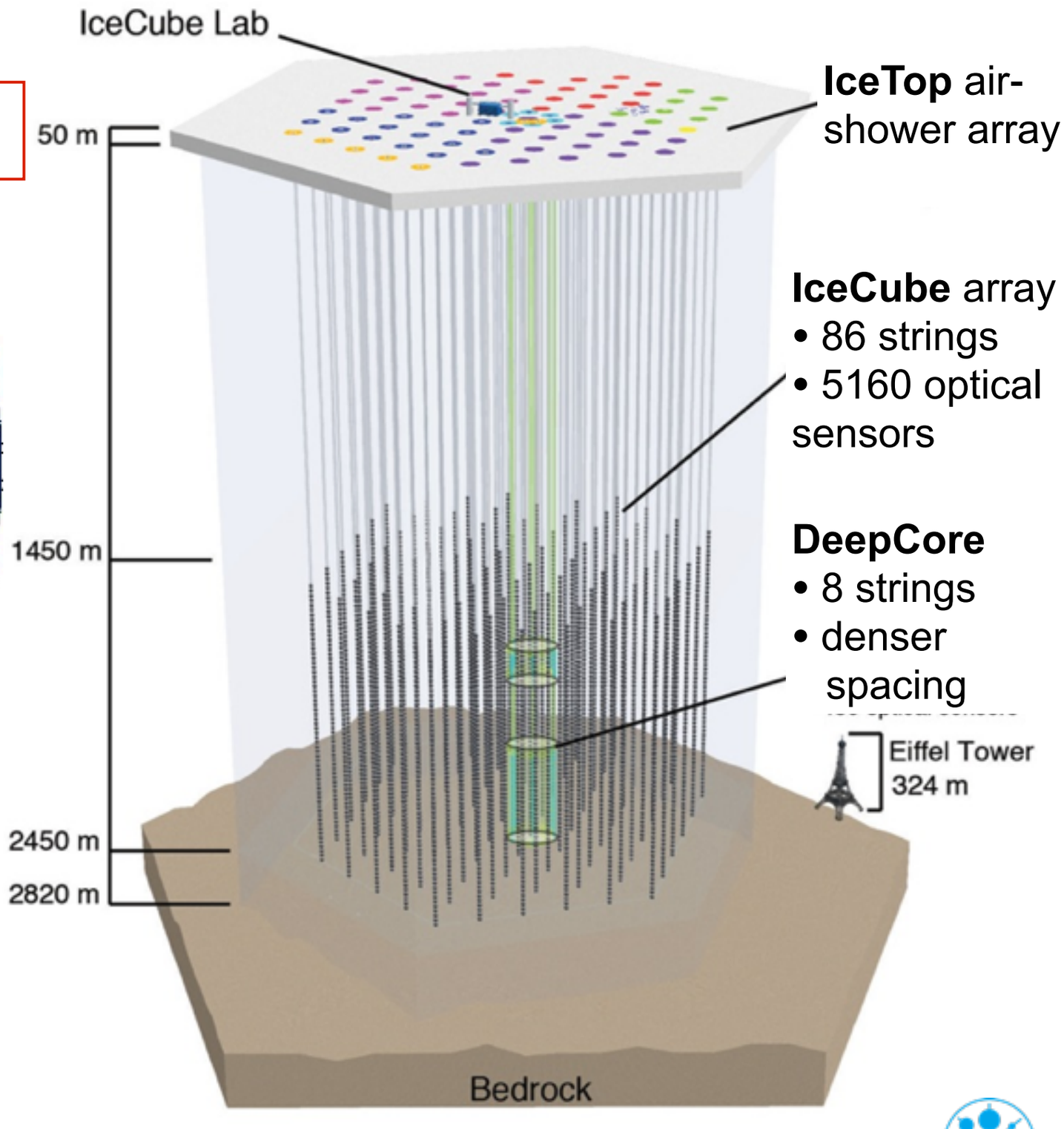




- Mediterranean sea, off **Toulon, France**
- **Operating since 2008** in final configuration
- 885 PMTs on 12 strings (~**10^{-2} km^3** instrumented volume)

Operating neutrino telescopes: IceCube

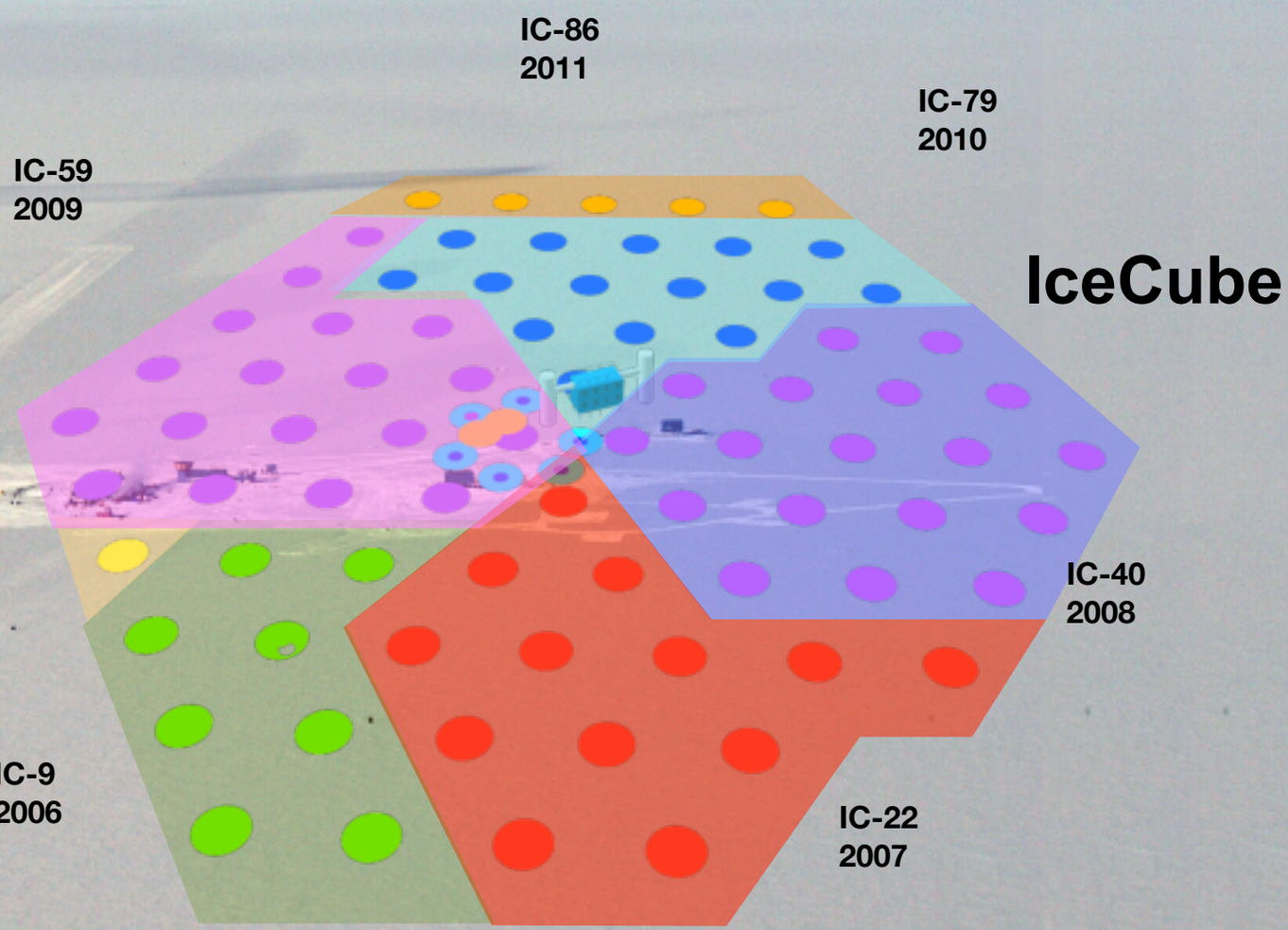




- **Completed** in Dec **2010**.
- Instrumented volume: **~ 1km^3**

Construction of the IceCube observatory.

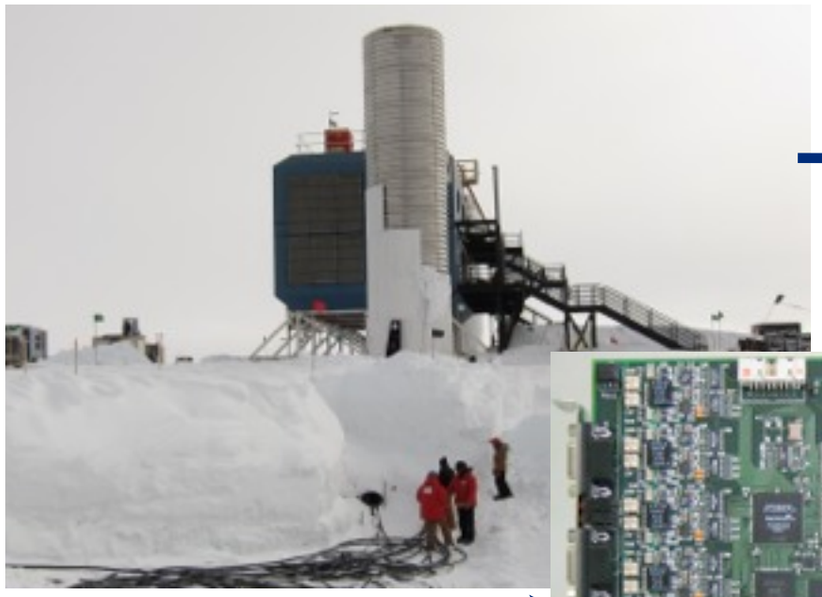
South Pole Station Building



- Construction period:
  6 years (2005-2010)
- Physics data from partially operating detector since 2007.

IceCube detector elements.

IceCube Laboratory
DAQ
Online filtering
Transfer
Storage

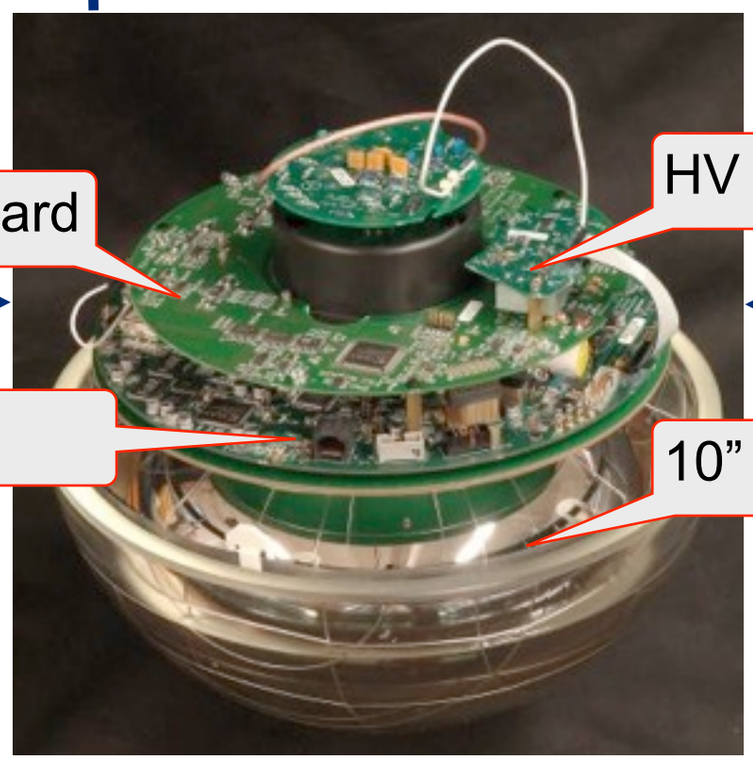


DOM receiver card

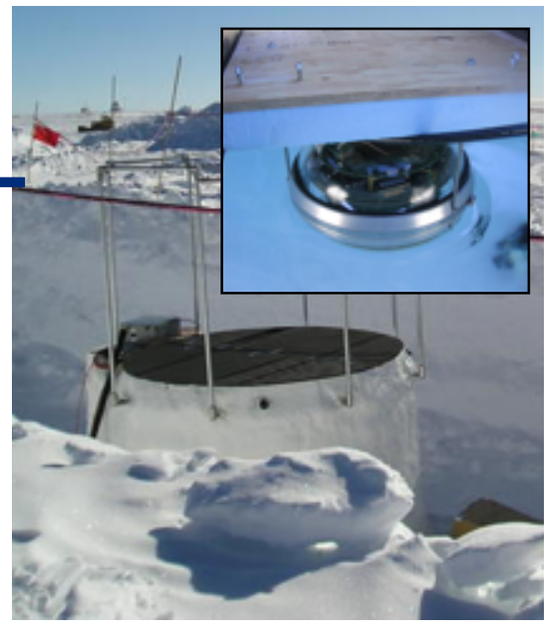
South Pole link to TDRSS satellite network

InIce Array
86 strings
60 DOMs per string

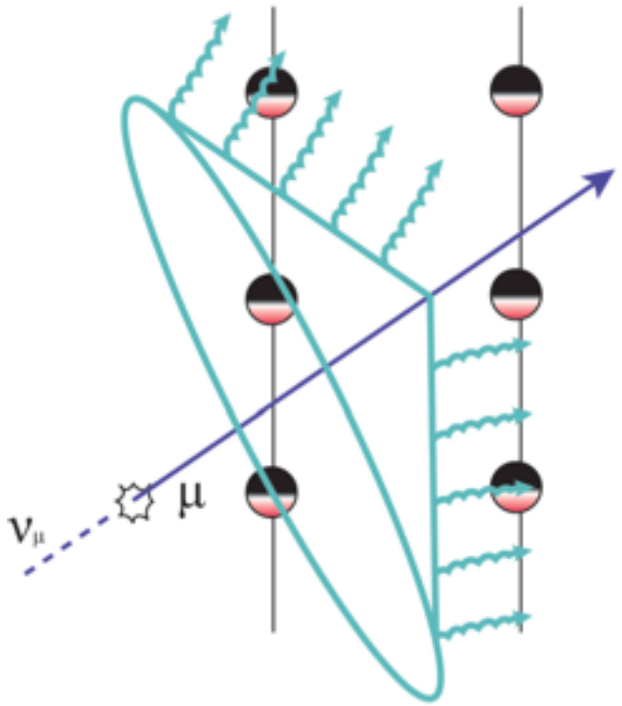
Digital optical module (DOM)



IceTop Array
81 stations
2 tanks per station
2 DOMs per tank

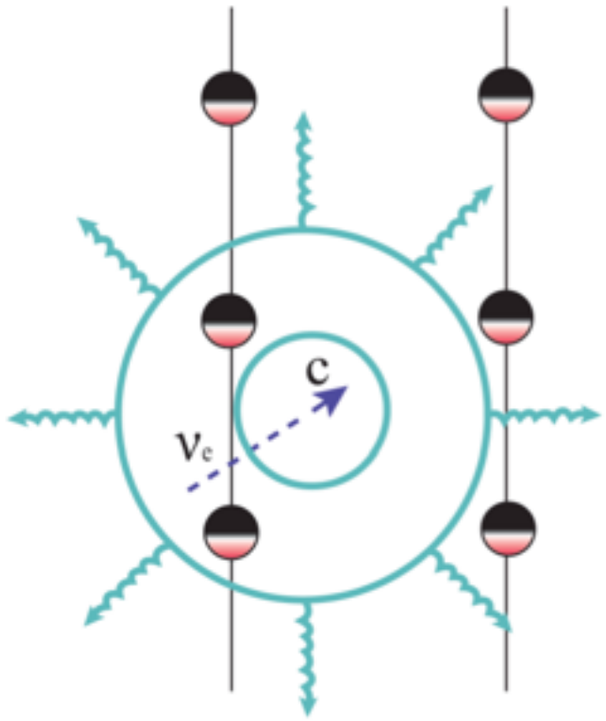


Detection of high-energy neutrinos.



> **Track-like event** signatures
(CC interactions of ν_μ)

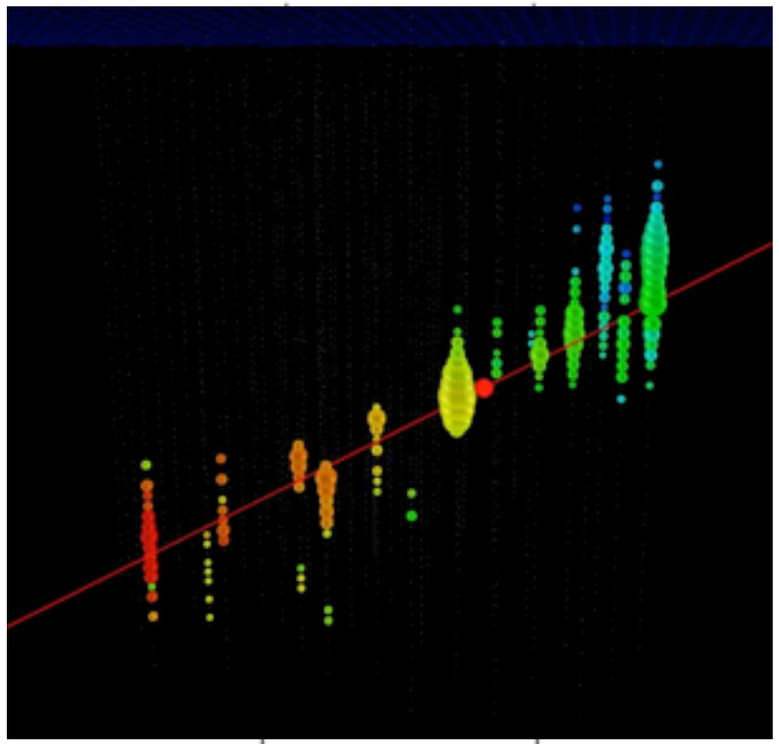
- **Angular** resolution: < 1°
- μ travels up to several km --> **interactions outside** the instrumented volume **visible**
- **Energy** resolution: dE/dx of the produced μ only.

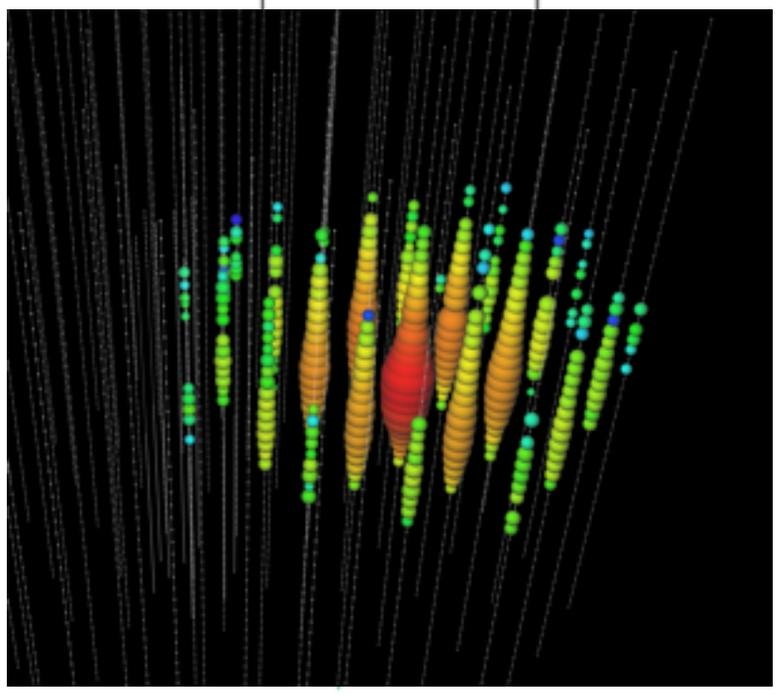


> **Shower-like event** signatures
(CC interactions of ν_e,ν_τ, NC interactions)

- **Angular** resolution: > 10°
- only **interactions inside** / close to the instrumented volume **visible**
- **Energy** resolution: up to 15% of neutrino energy.

Detection of high-energy neutrinos.





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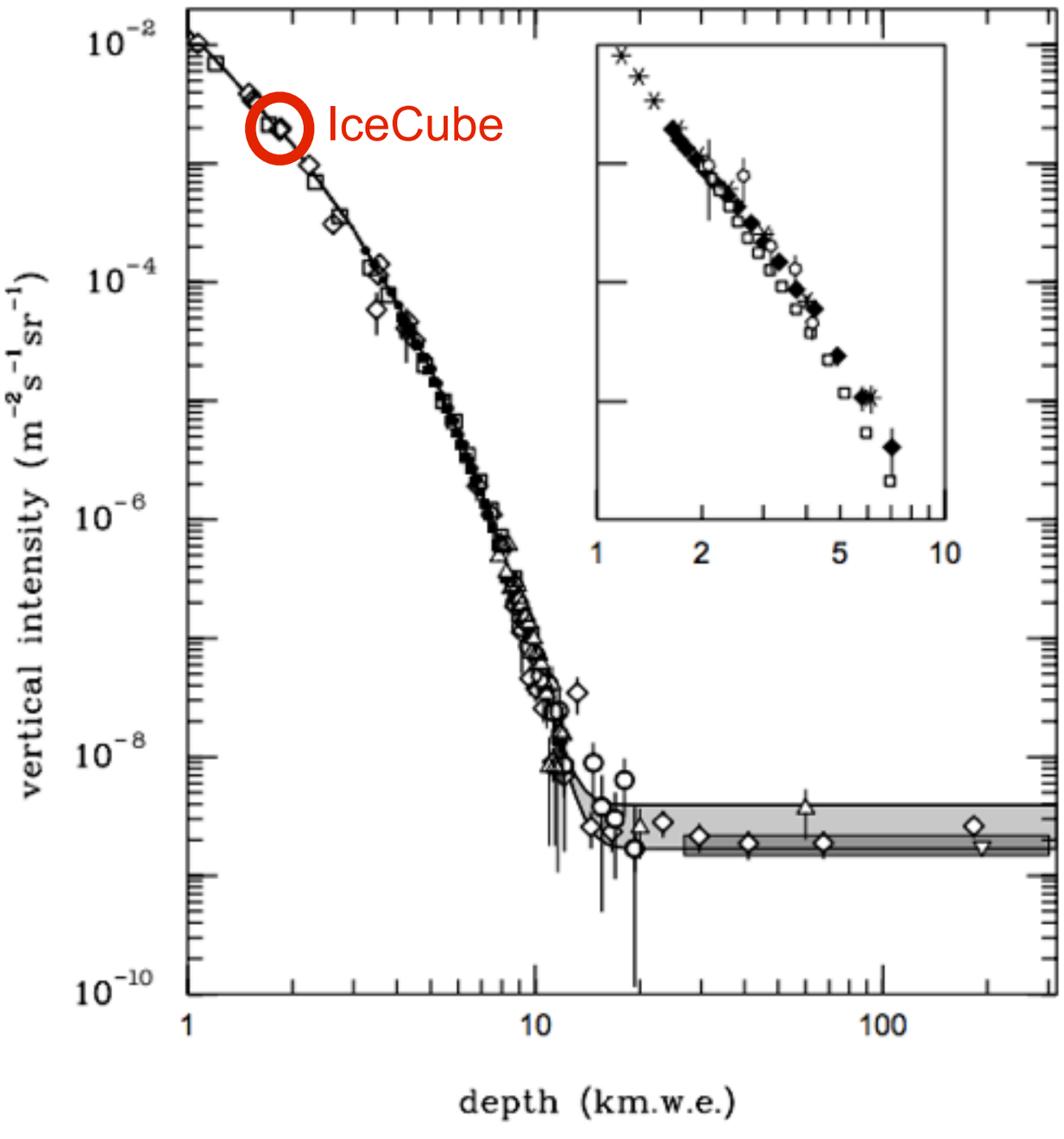
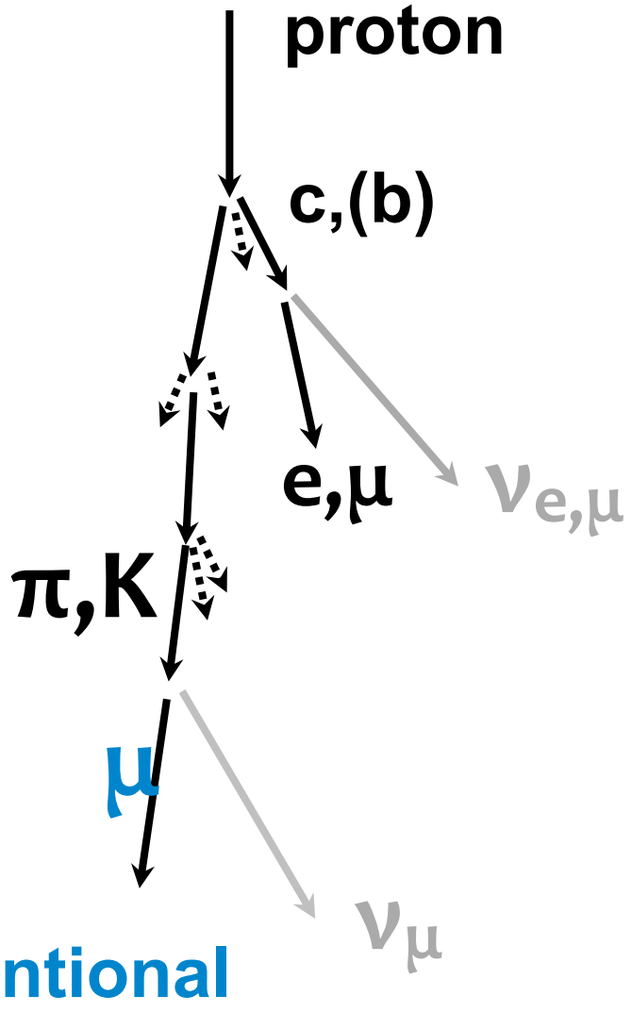
- **Energy** resolution: up to 15% of neutrino energy.

Backgrounds: Muons from CR air showers.

- **Muons from CR air showers** account for 99.9999% of all events seen by IceCube.
- Restricted to **Southern hemisphere.**

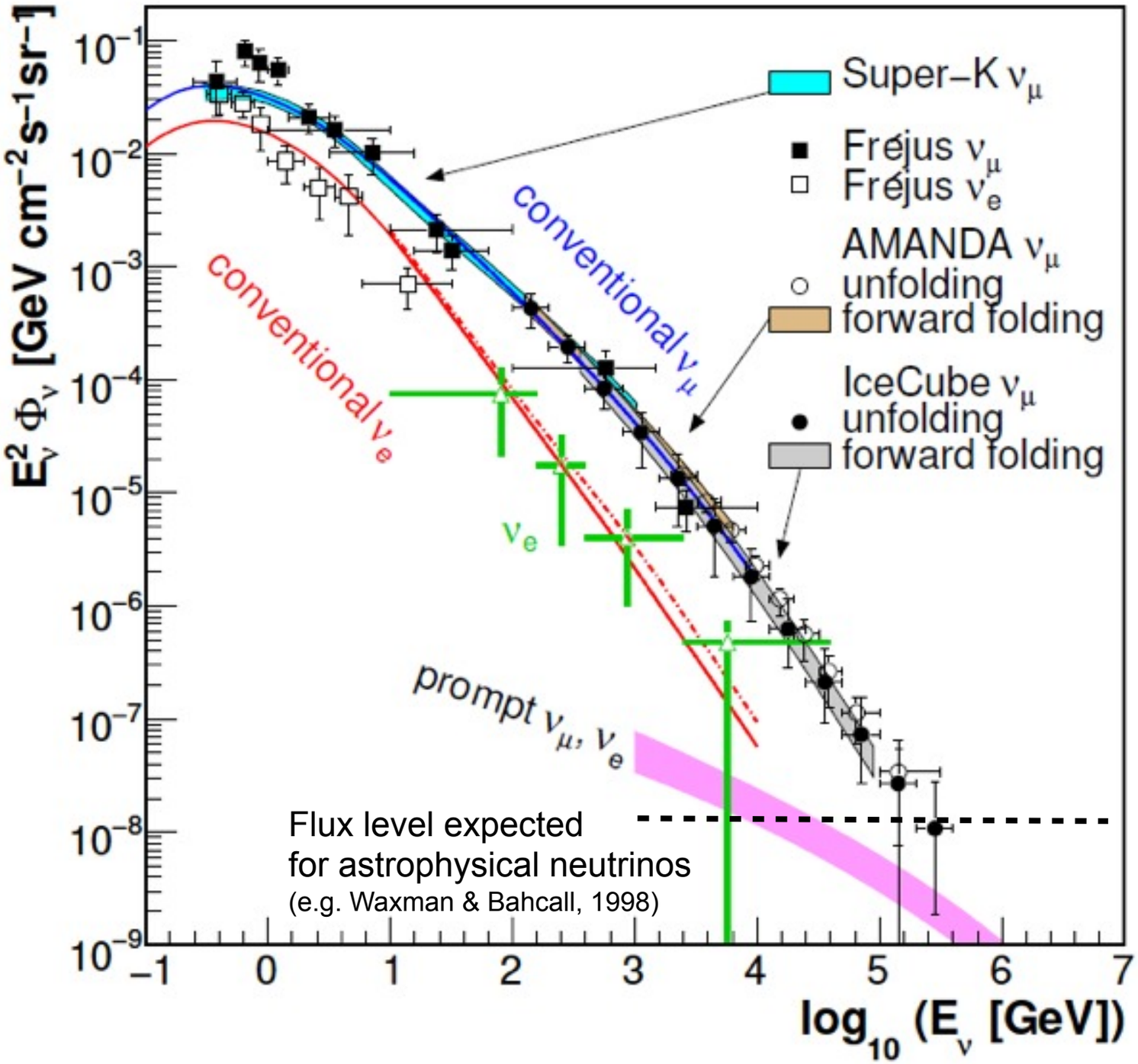


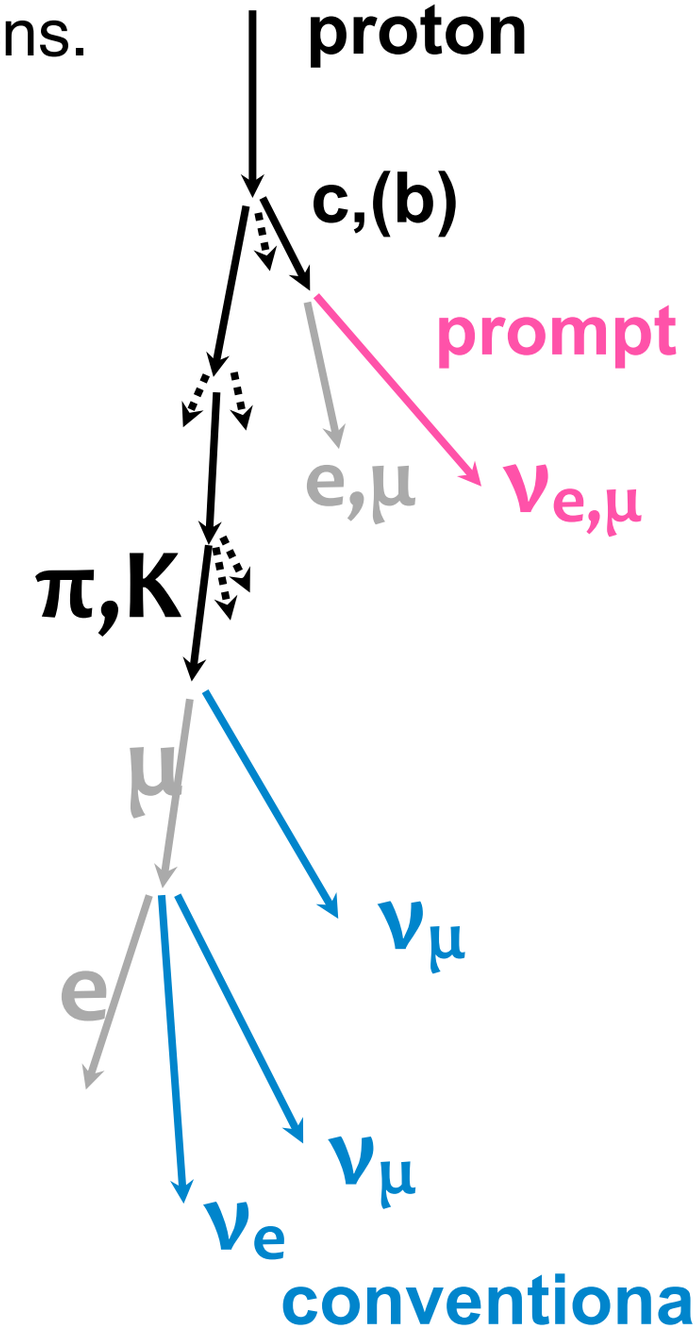


Muon intensity as function of depth.

Backgrounds: Atmospheric neutrinos.

- **Most neutrinos** seen by neutrino telescopes are of **atmospheric origin**.
- Atmospheric-ν are produced in **CR air shower interactions**.
- **"Prompt" component** from the decay of charm mesons.

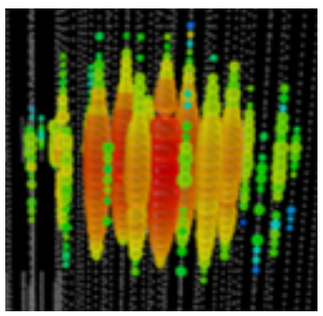




Particle physics and astrophysics with IceCube.

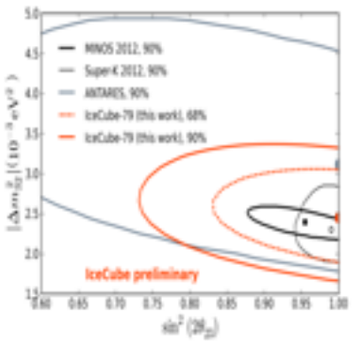
> Search for **astrophysical sources** of high-energy **neutrinos**.

- Galactic and extragalactic sources.
- Transients (Gamma-ray bursts, flares of AGNs, periodic emission from binaries).
- Neutrinos from WIMP annihilation in the sun.



> Measurement of the **diffuse neutrino flux** from the universe

- from unresolved sources
- from the interactions of ultra-high-energy CR

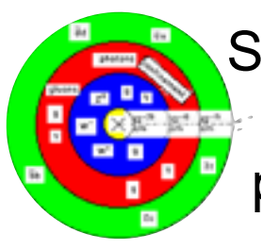


> Measurement of **neutrino properties** using atmospheric neutrinos

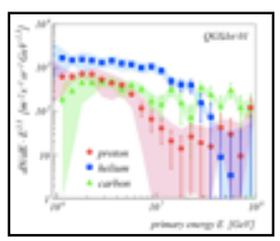
- Measurement of oscillation parameters
- Sensitivity to sterile neutrinos

NOT covered in this talk: all the other great science with neutrino telescopes.

MeV neutrinos from SN



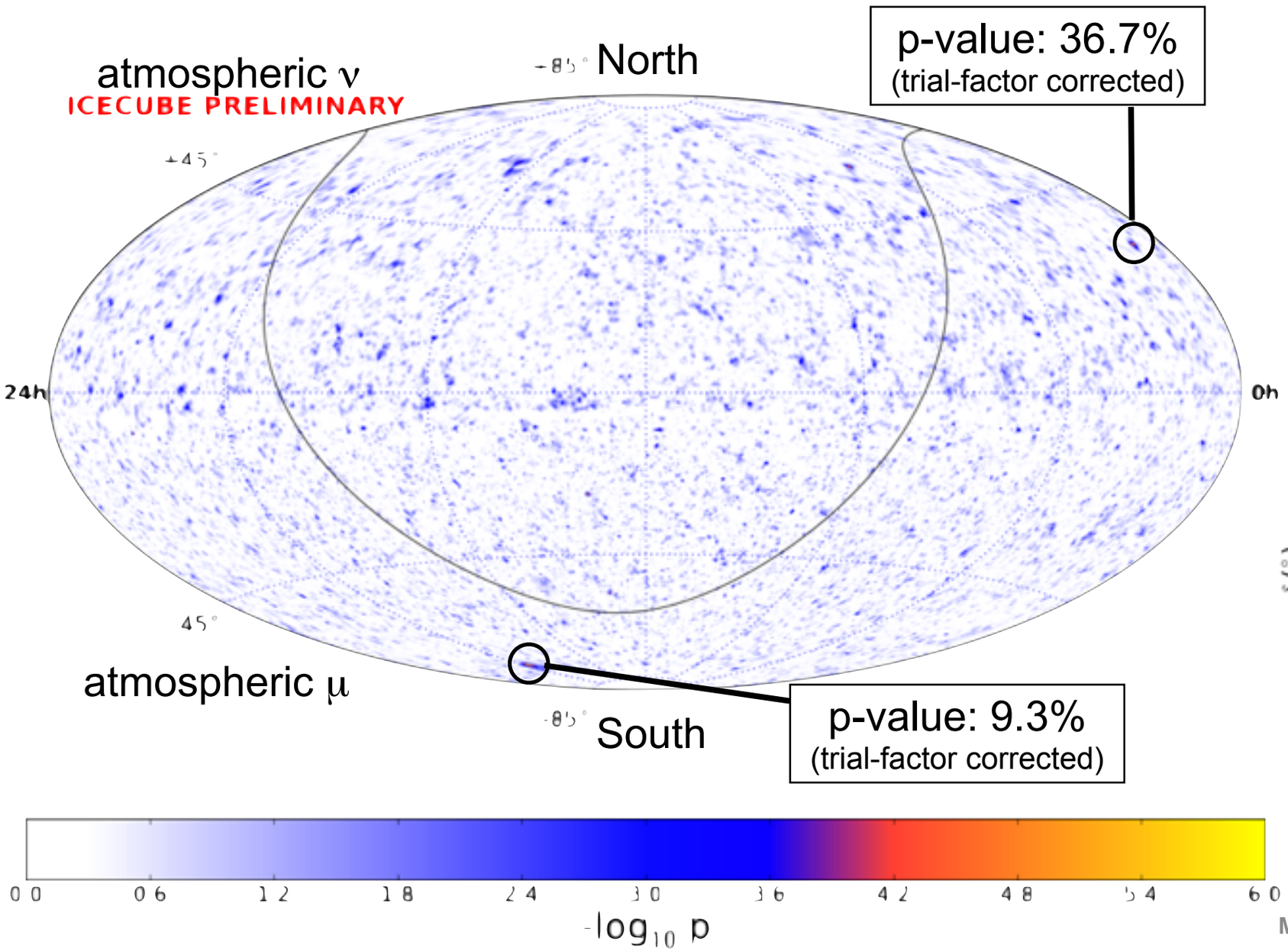
Search for exotic particles

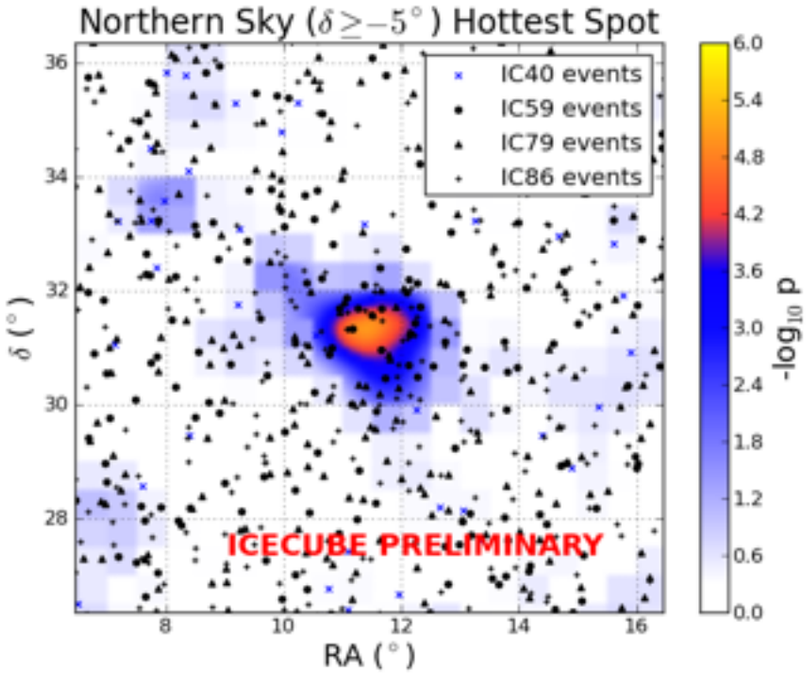


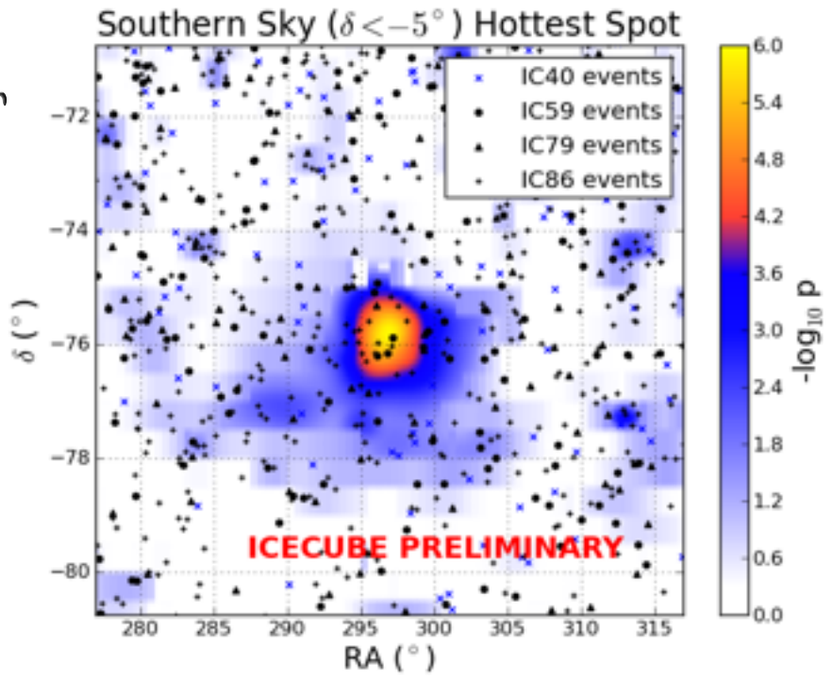
CR physics ....

Search for individual neutrino sources: IceCube

- **4 years** of IceCube data (construction phase + full array)
- 1371 days of livetime, **394,000 events** total
  - **178,000 neutrino** candidates in the North
  - **216,000 atmospheric muons** in the South



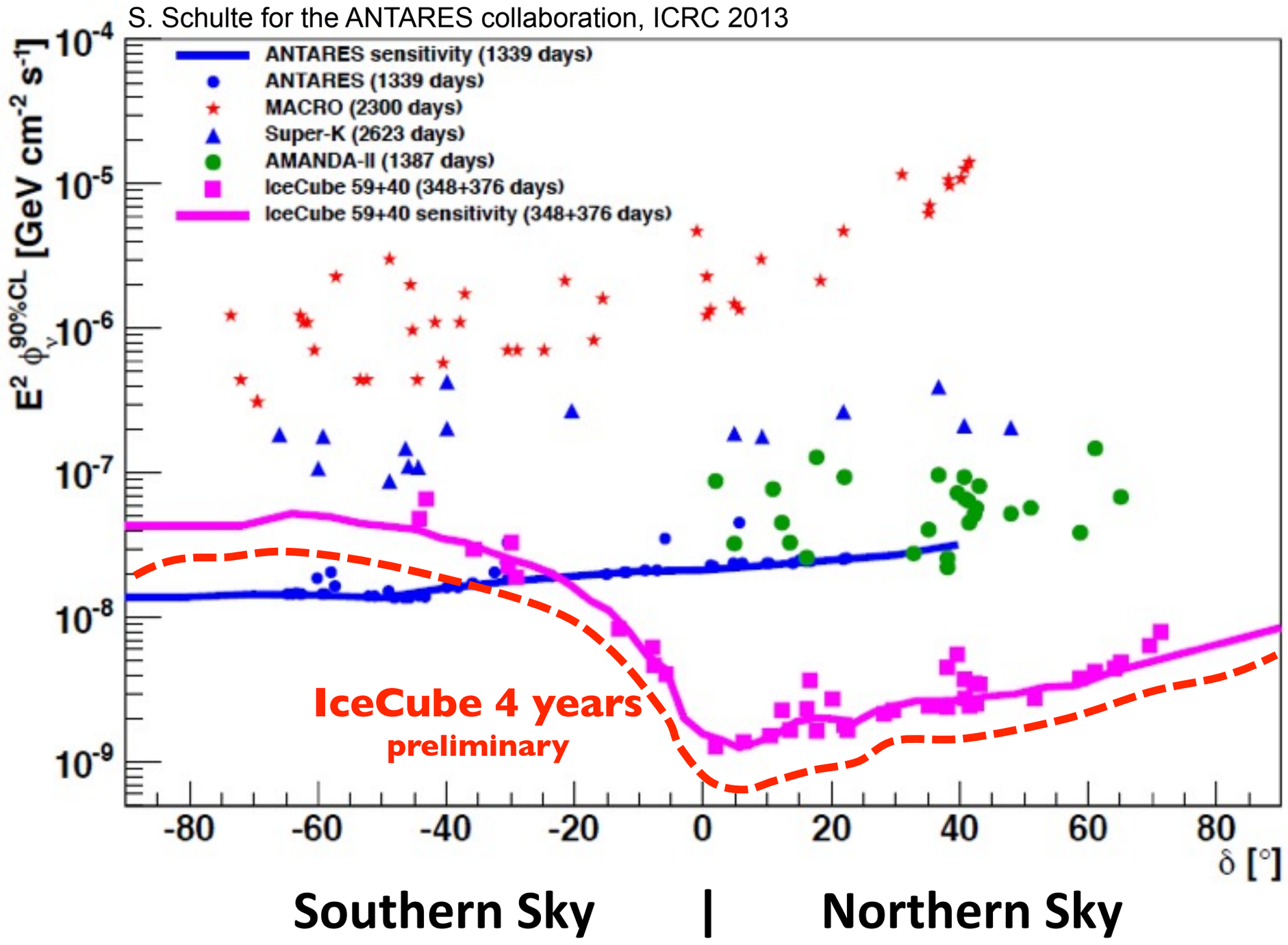




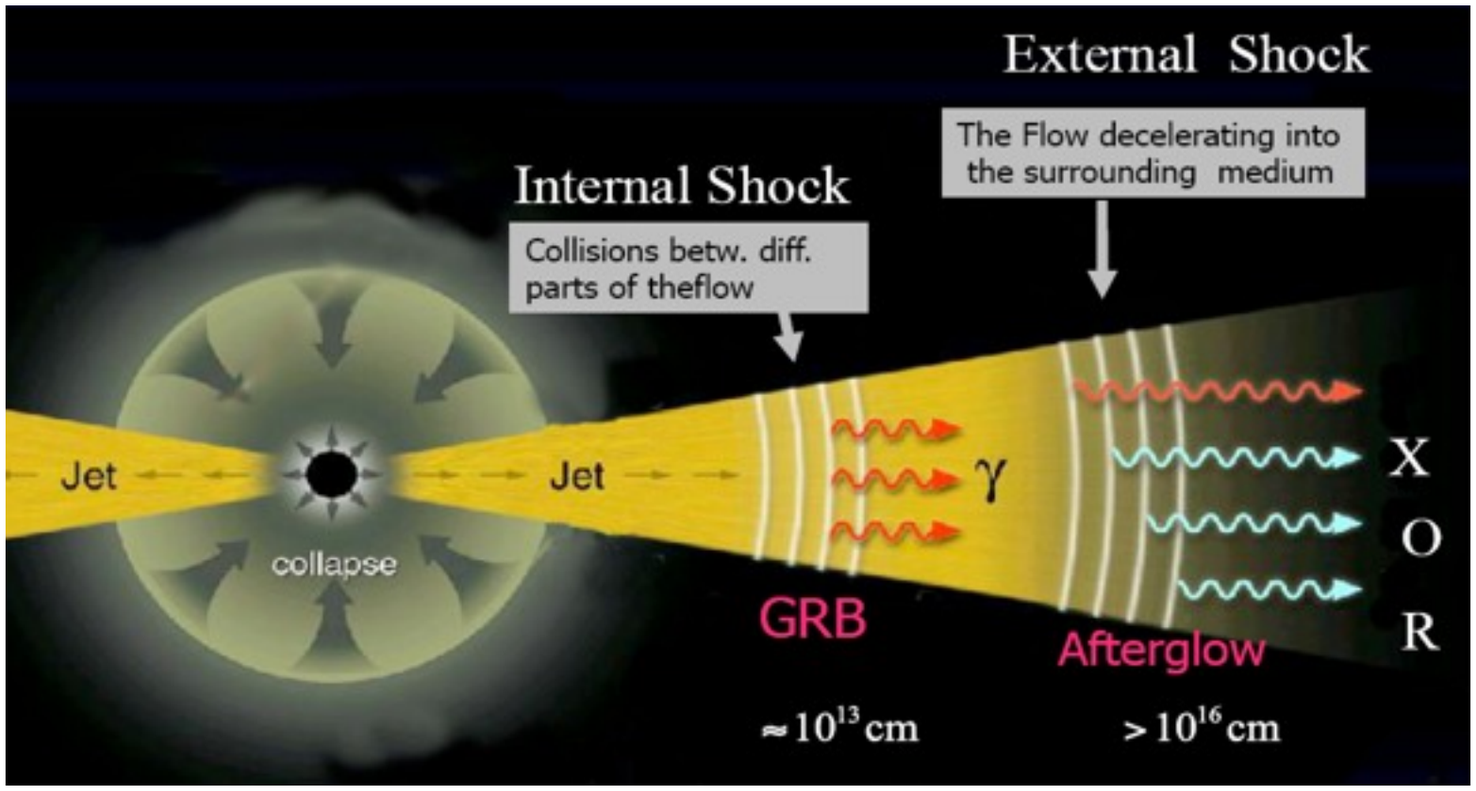
Upper limits on the neutrino flux from sources.

- **Factor 1000 increase** in sensitivity over 13 years.
- **No detections.**
- **ANTARES and IceCube** observations are **complementary**.

S. Schulte for the ANTARES collaboration, ICRC 2013

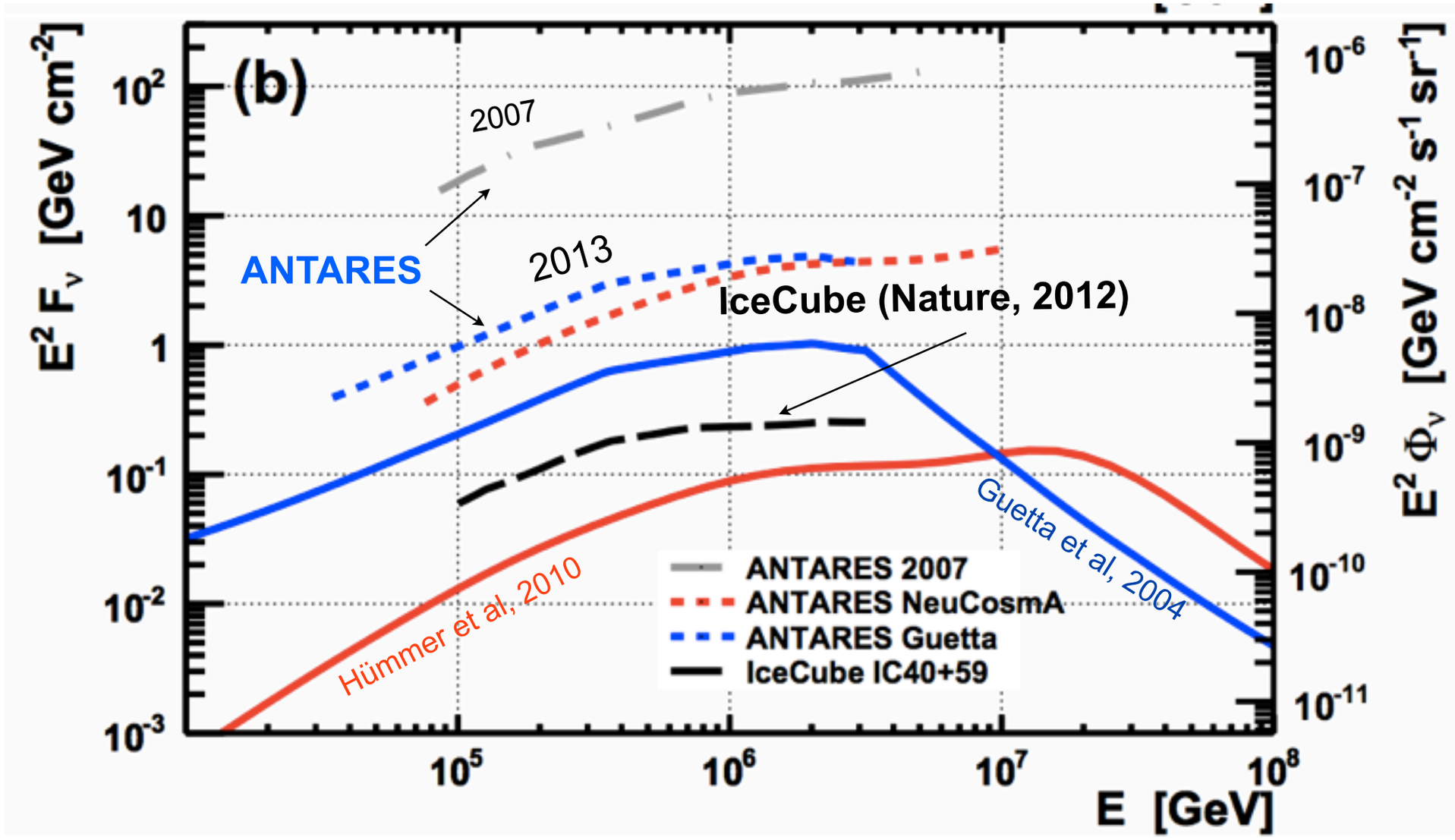


Search for neutrinos from transients: GRBs



- **GRBs** have been proposed as the **dominant acceleration site** for CRs up to energies > 10^{20} eV.
- Accompanying **neutrino emission** should be **visible in km³-sized** neutrino telescopes in a wide variety of scenarios.
- Search for **cumulative signal** from all observable bursts.

Search for neutrinos from GRBs.



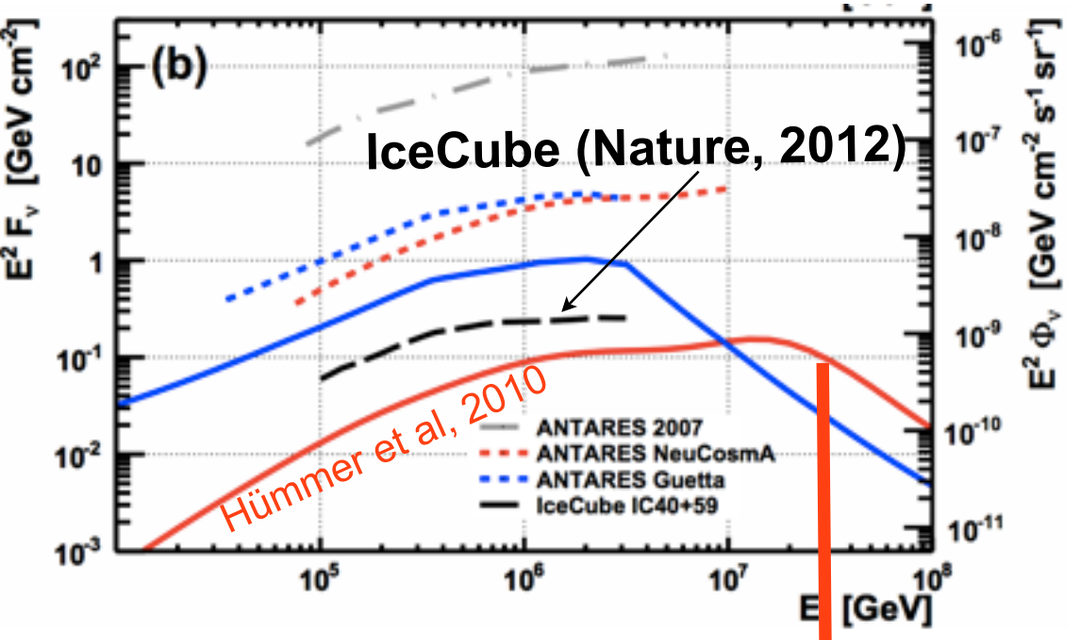
IceCube

- **225 GRB** at Northern sky
- 2 years of IceCube construction phase data
- No significant correlation found between IceCube events and GRBs.

ANTARES

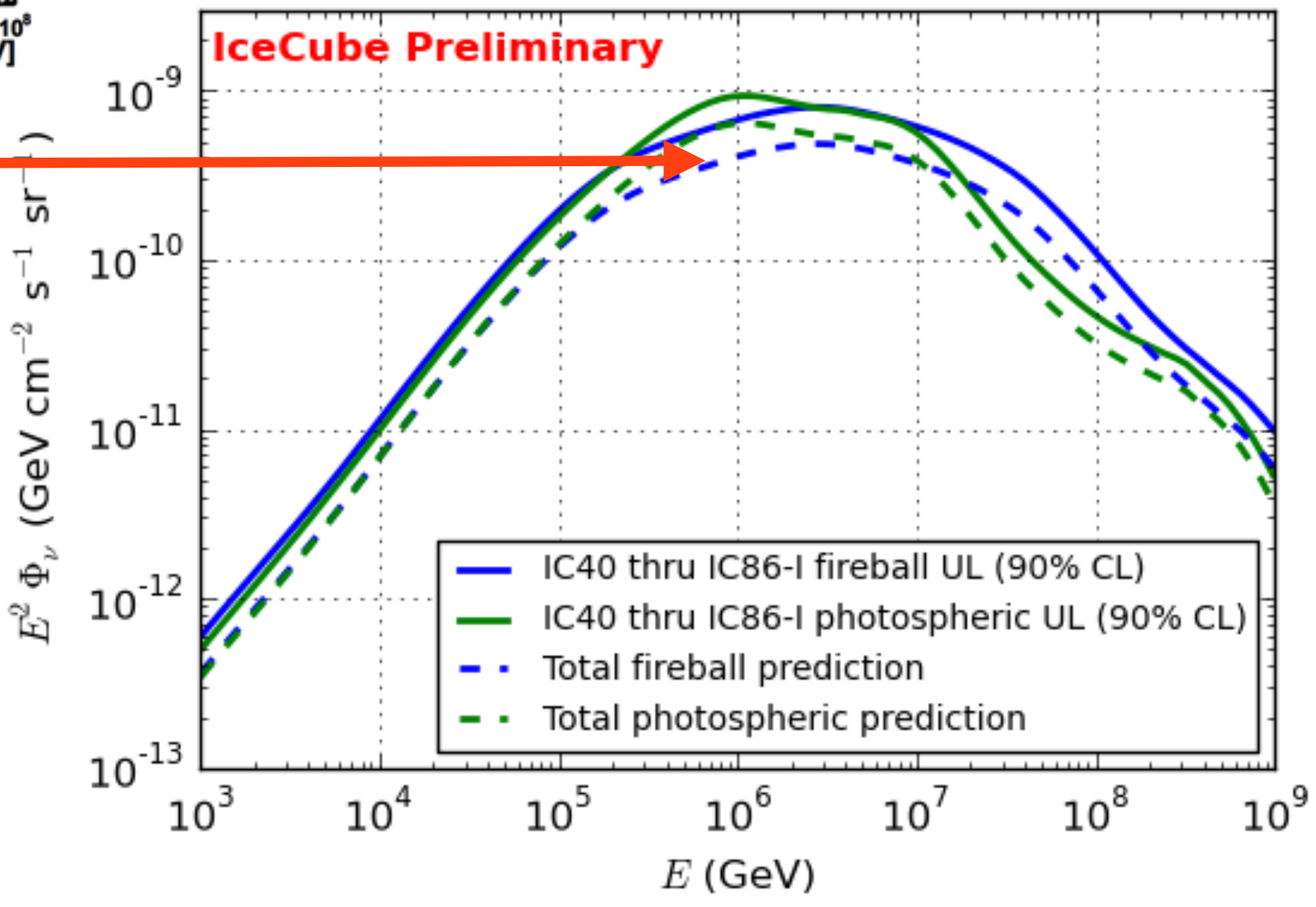
- **296 GRB at** Southern sky
- No ANTARES event in time and direction coincidence (arXiv:1307.0304)

Search for neutrinos from GRBs.



- Neutrino flux prediction is individually modeled for each GRB
- More sophisticated calculations of neutrino production in GRBs lead to a lower flux prediction.

- **New upper limits** from the analysis of 568 GRBs (4 years of IceCube data)
- Limits close **to corrected flux** predictions.



Searches for other transients.

- Specific searches for transient enhance the sensitivity through improving signal/noise.

- Flares o**f Active Galactic Nuclei**:
  - Correlation with Fermi light curves
  - ToO observation program with IACTs.

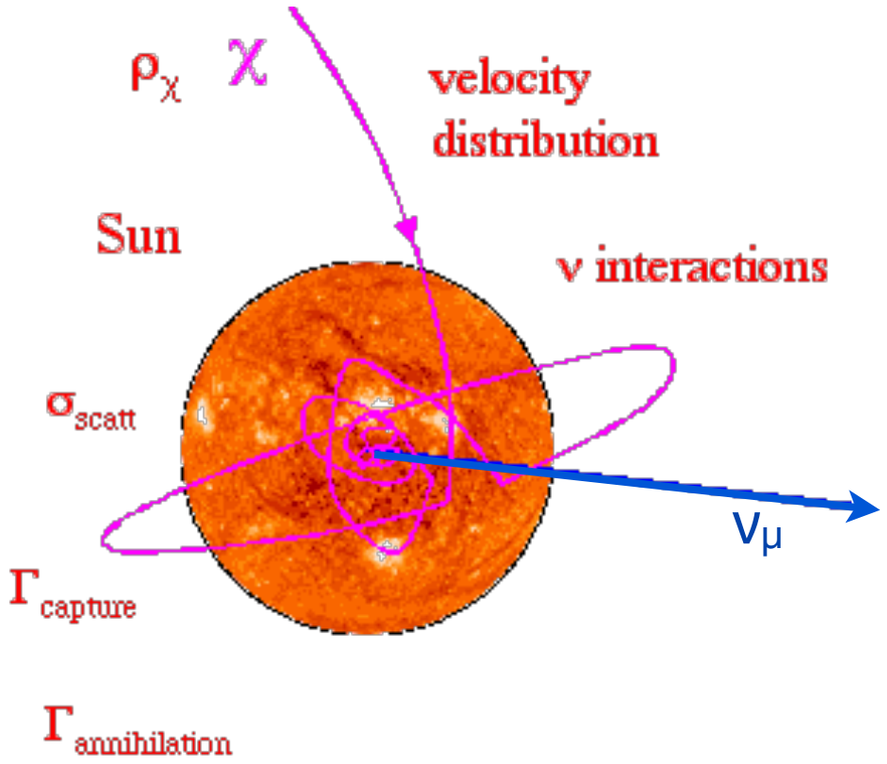
- **Periodic sources** / Binaries:
  - Phase resolved analysis of neutrino events from periodic sources.

- GeV/TeV neutrinos from **extragalactic SNe**:
  - Neutrino-triggered follow-up observations with optical telescopes.

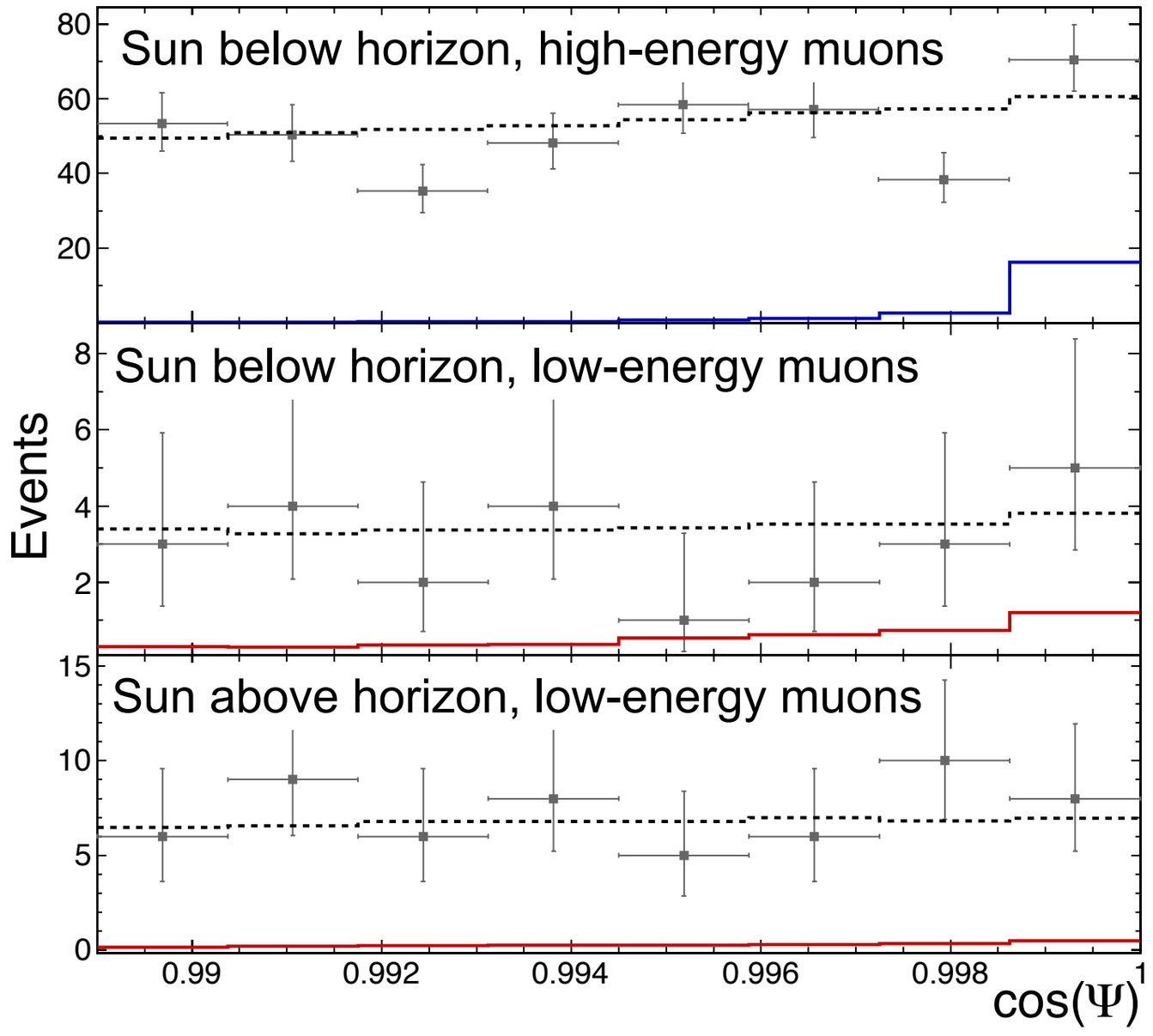
- The **unexpected**:
  - Search for space/time clustering of neutrino events.

- **No significant detection** yet in any of these searches.

Search for neutrino annihilations in the sun.

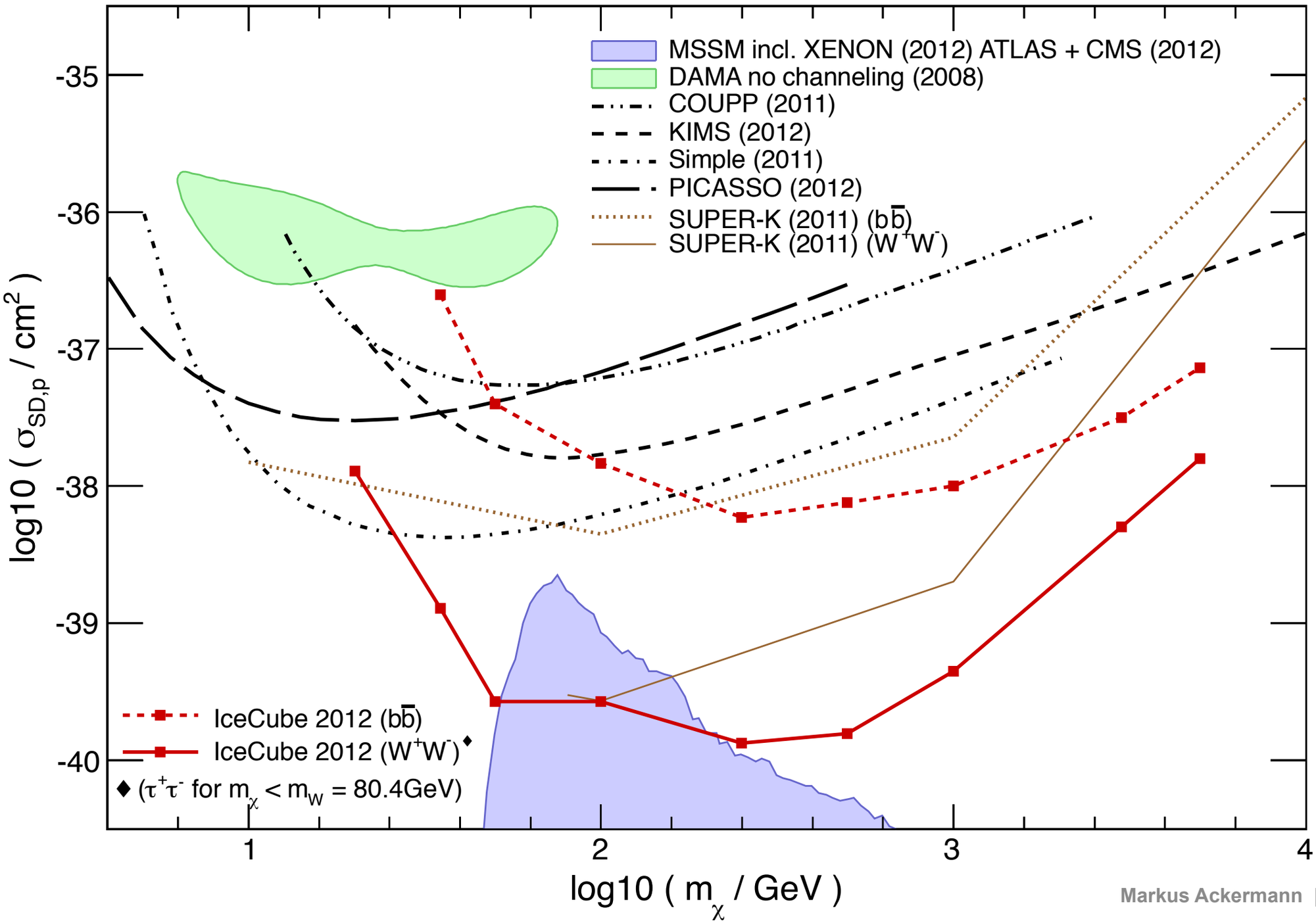


- Neutralinos get captured by scattering off atoms in the Sun.
- Annihilation of accumulated WIMPs produces neutrinos.
- In equilibrium: Neutrino flux depends only on scattering cross section.

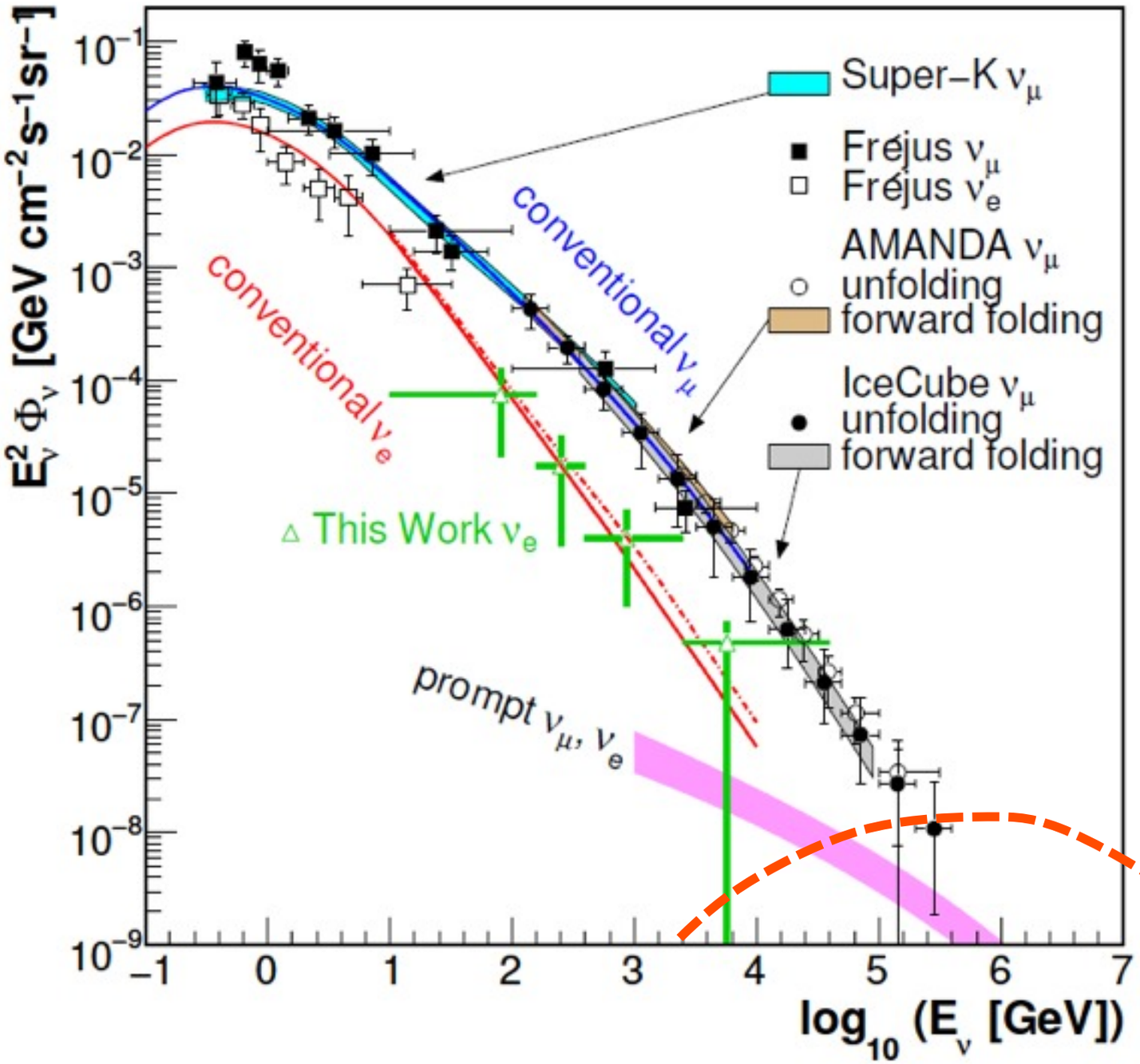


Search for neutrino annihilations in the sun.

- Mass of sun is dominated by hydrogen atoms.
- World's best limits on spin-dependent cross-section from IceCube.



Search for diffuse astrophysical neutrinos.



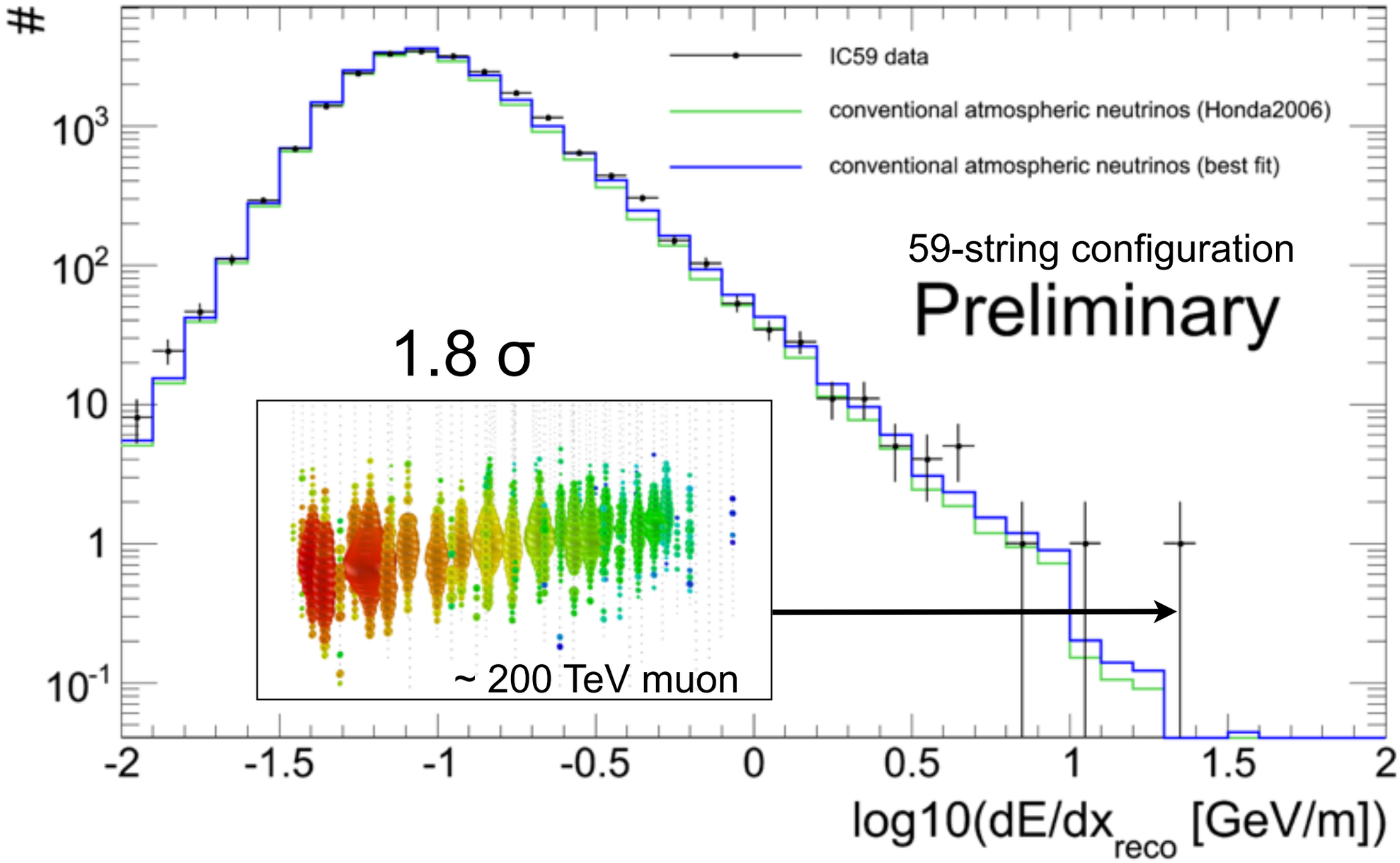
> Search for a **diffuse excess** of neutrinos over background from atmosphere at high energies.

- From unresolved neutrino sources
- From the interactions of CR with the extragalactic background light

> **Lower** atmospheric **background** for **shower-type** events (ν_e + NC ν_μ only)

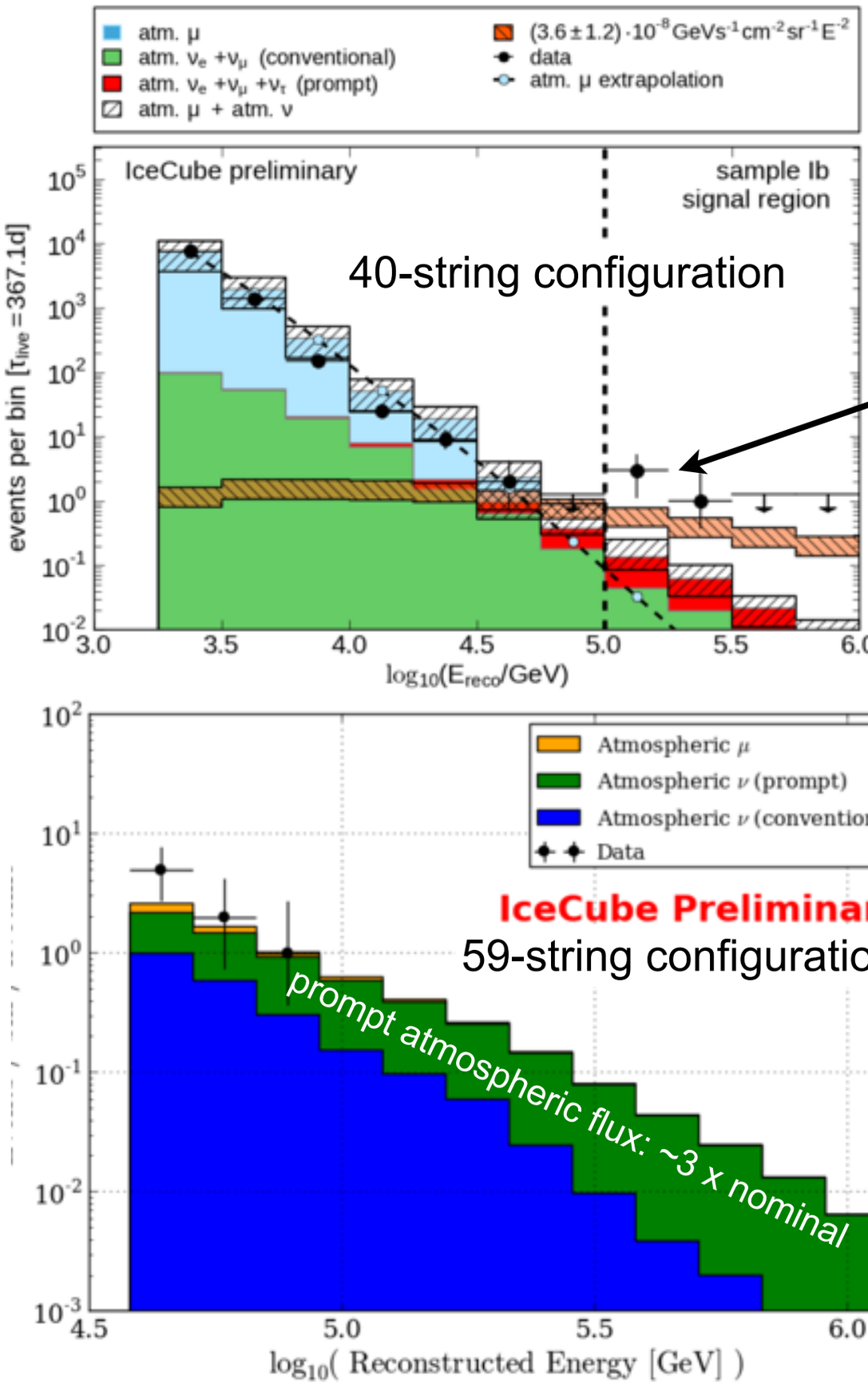
extraterrestrial neutrinos ?

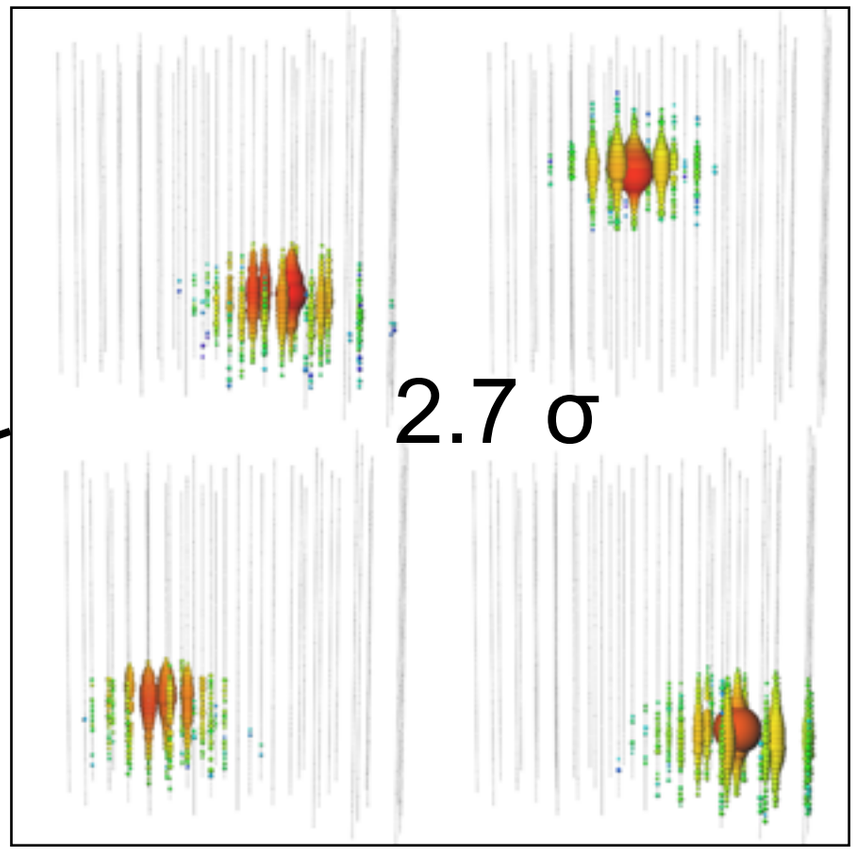
Search for diffuse astrophysical neutrinos: Construction phase.



- Search for high-energy excess in the muon energy loss spectrum.
- Low-significance excess found in construction phase data.

Search for diffuse astrophysical neutrinos: Construction phase.

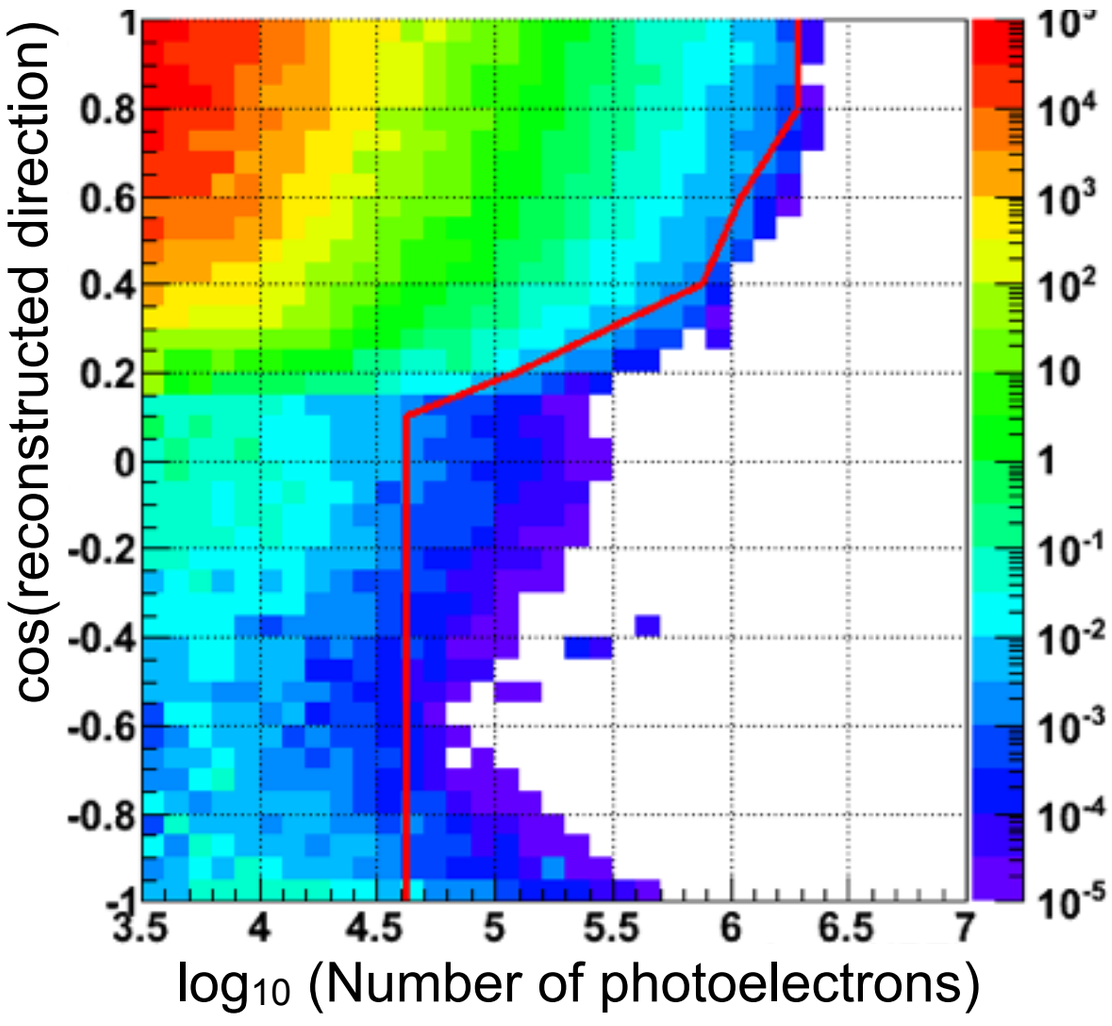


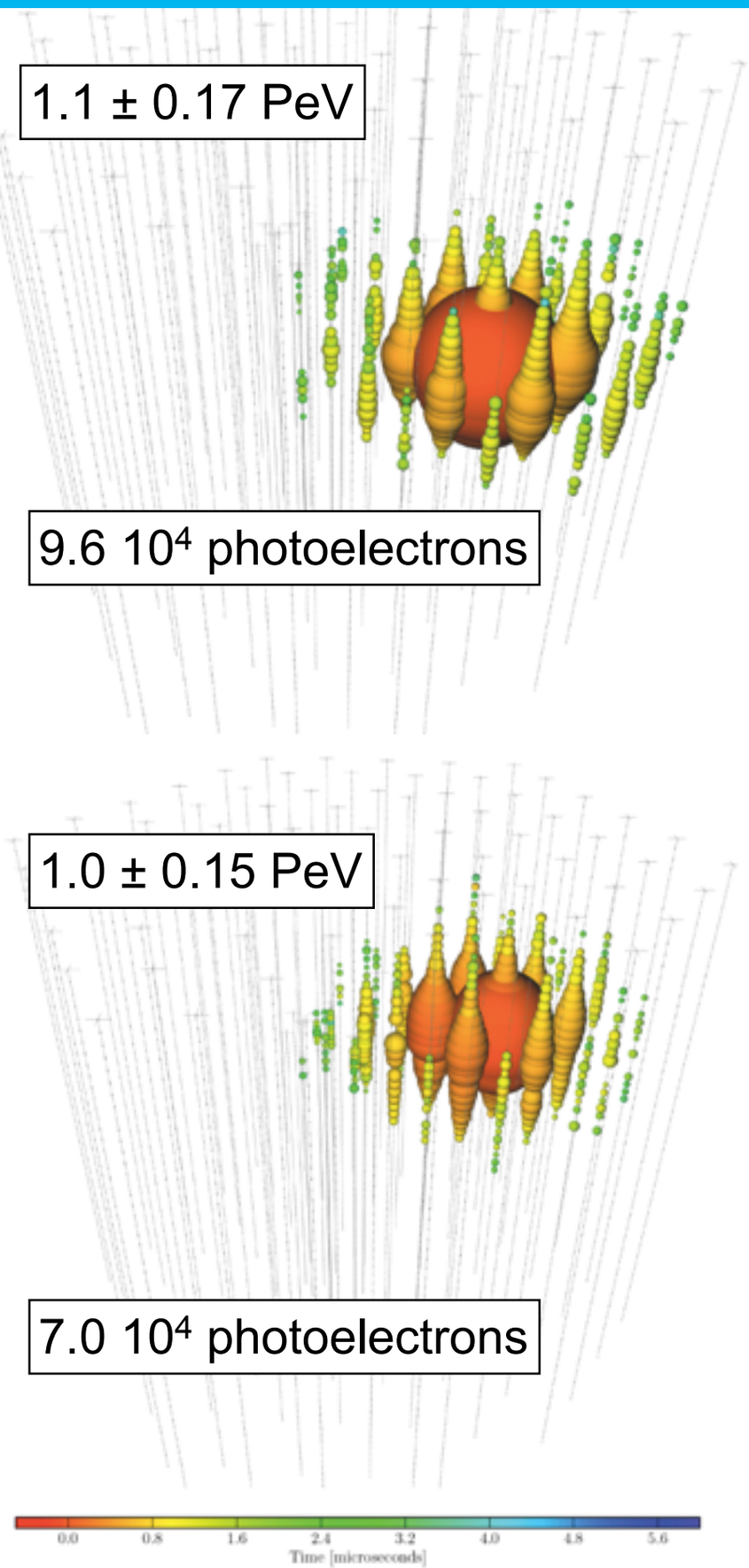


- **Excess events** observed in analysis of shower-like events.
  - 4 events observed above 100 TeV in 40-string configuration.
  - Excess of events in data from 59-string configuration (but compatible with background hypothesis within uncertainties)

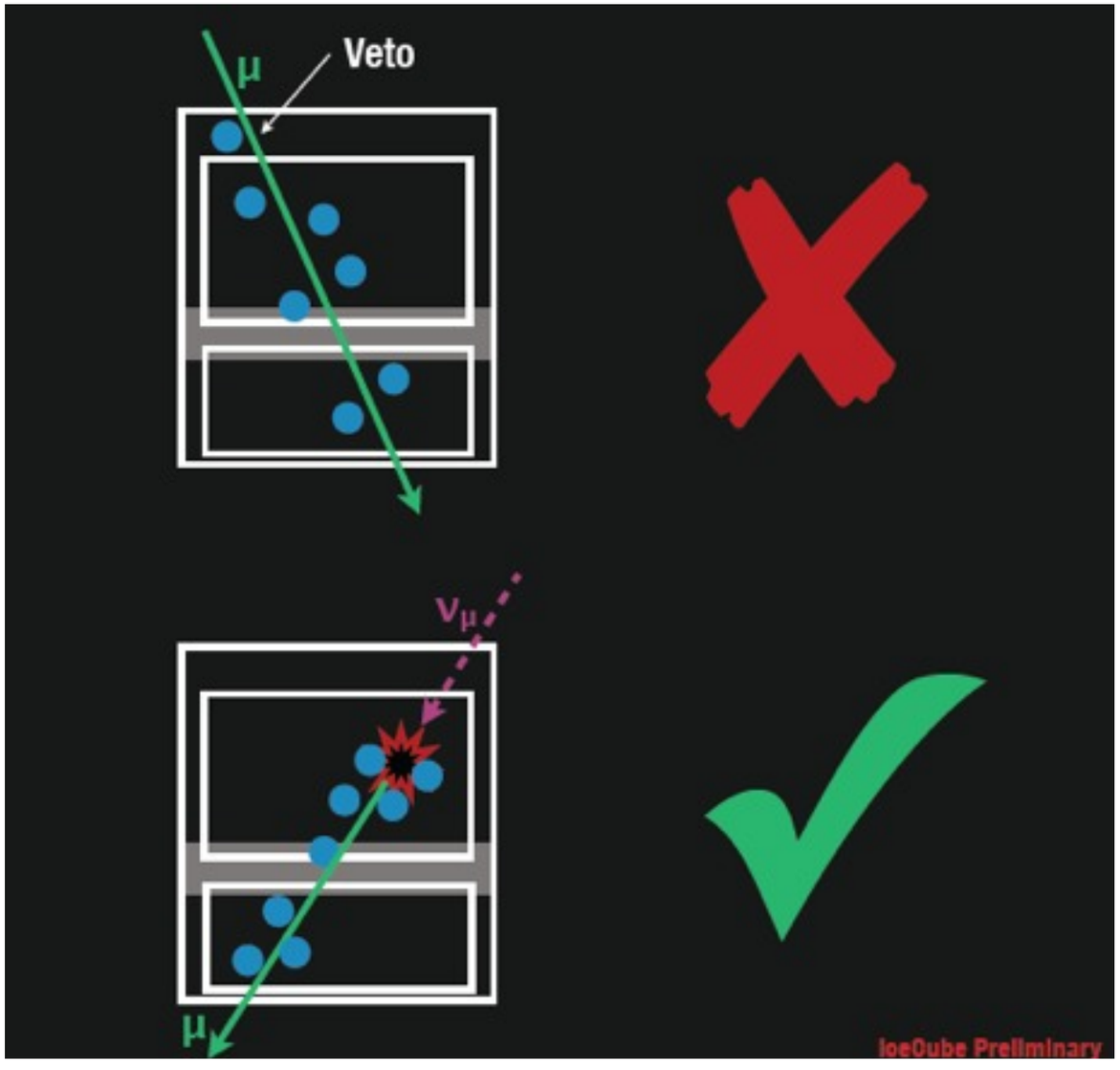
Search for bright events with 2 years of IceCube data.

- 79-string and 86-string configurations.
- **Optimized** for **cosmogenic neutrinos** of EeV energies.
  Cosmogenic = produced in interactions of ultrahigh-energy CR with the CMB/background light.
- **2 events** just above threshold.
- **2.8σ excess** above expected atmospheric-ν flux.

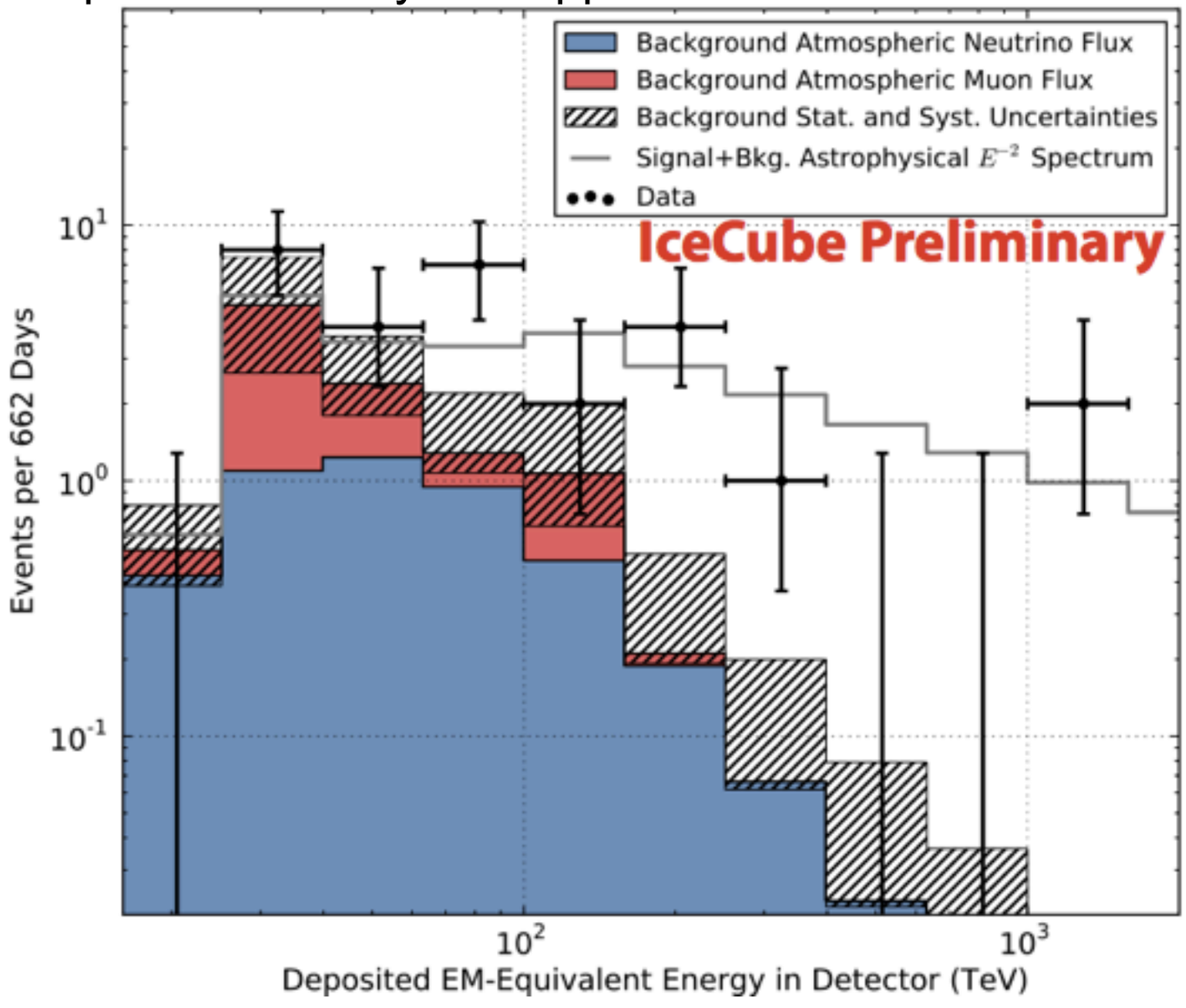




Search for a diffuse astrophysical flux.



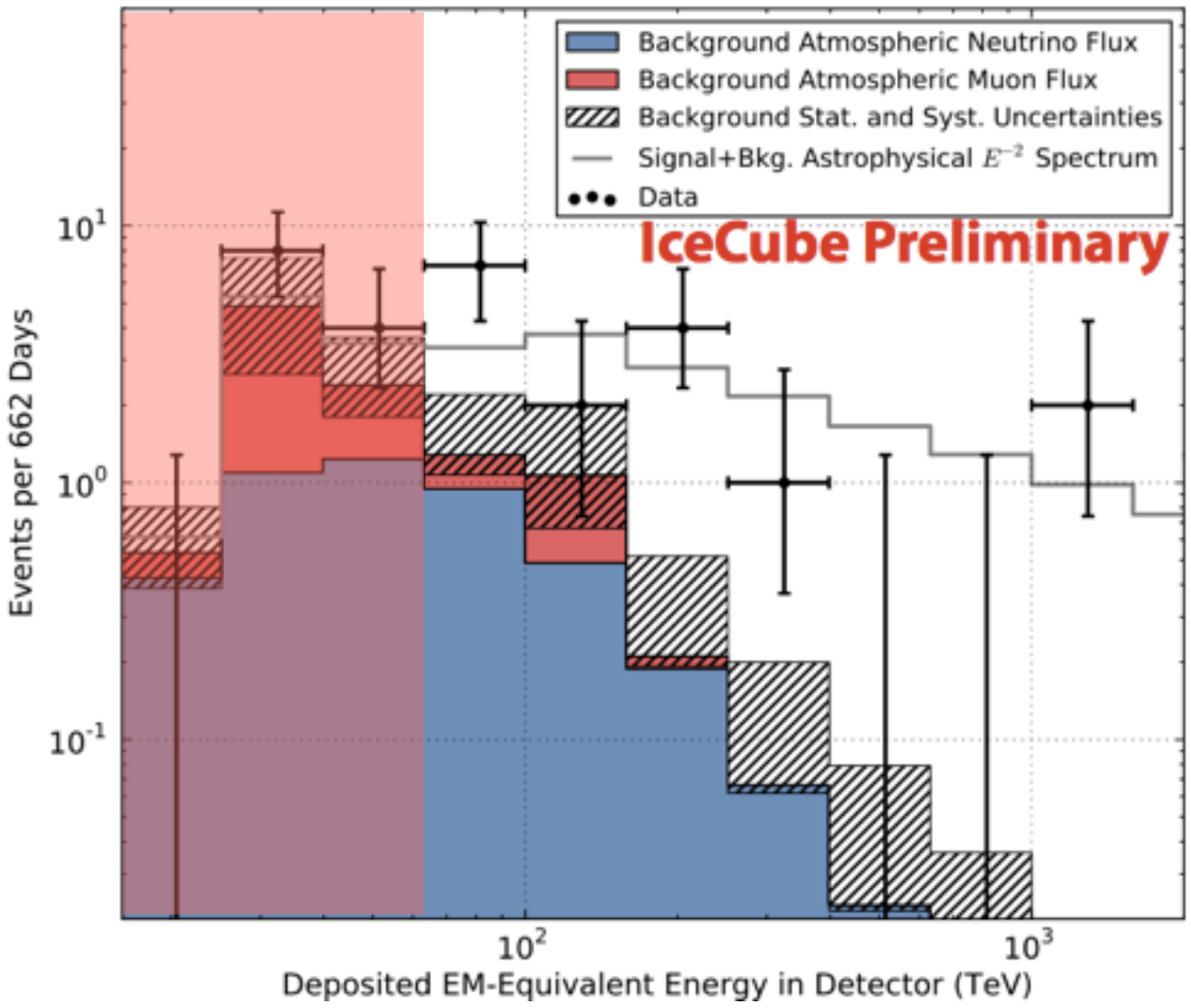
see presentation by C. Kopper



- **Extension** of previous search to **lower energies** (~ 30 TeV energy threshold)
- **New strategy** to reject CR background.
- **28 events** found in 2010-2012 dataset.
- **4.1σ excess** over expected backgrounds from atmospheric μ / ν

Spectral and angular distribution.

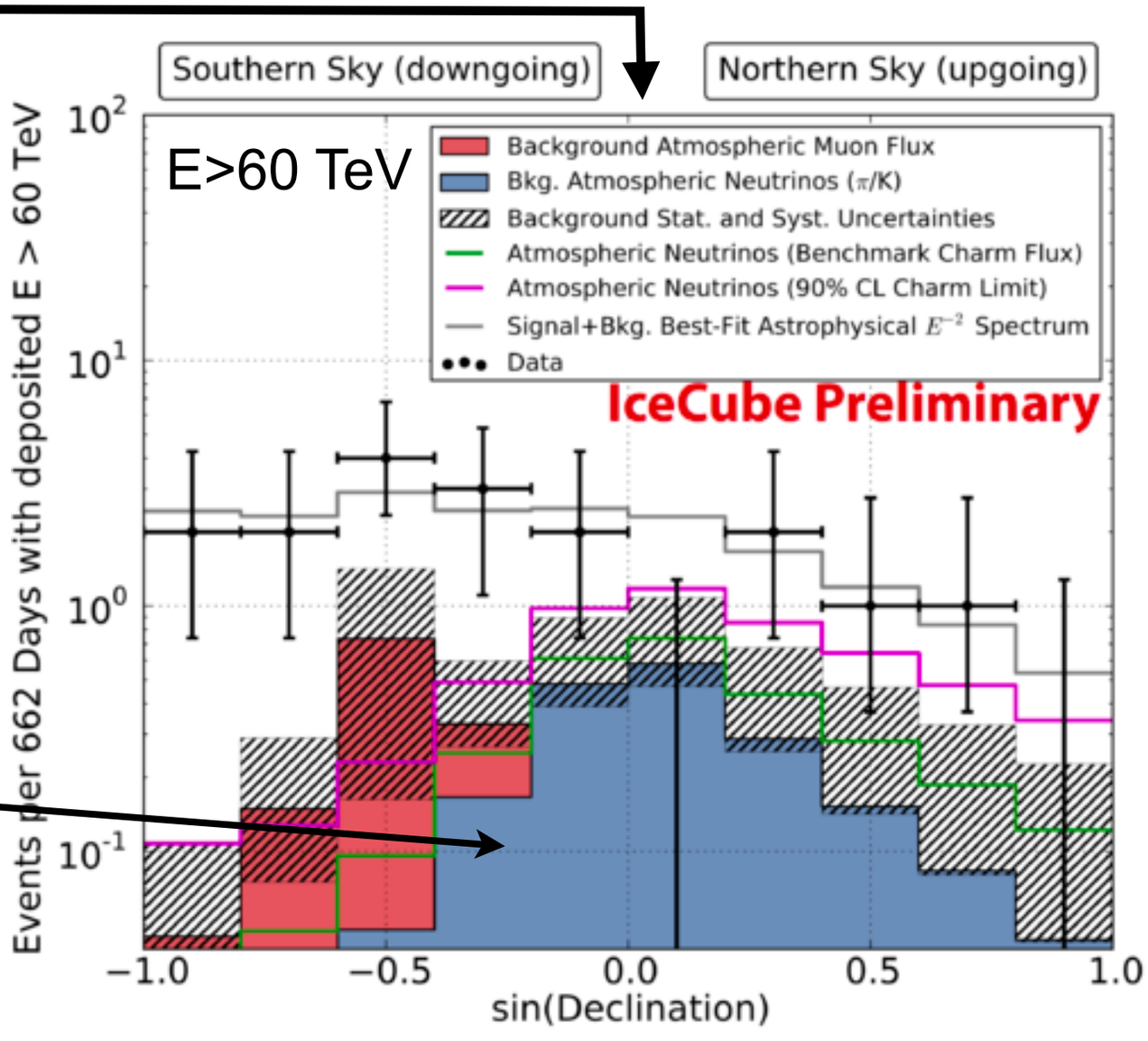
see presentation by C. Kopper



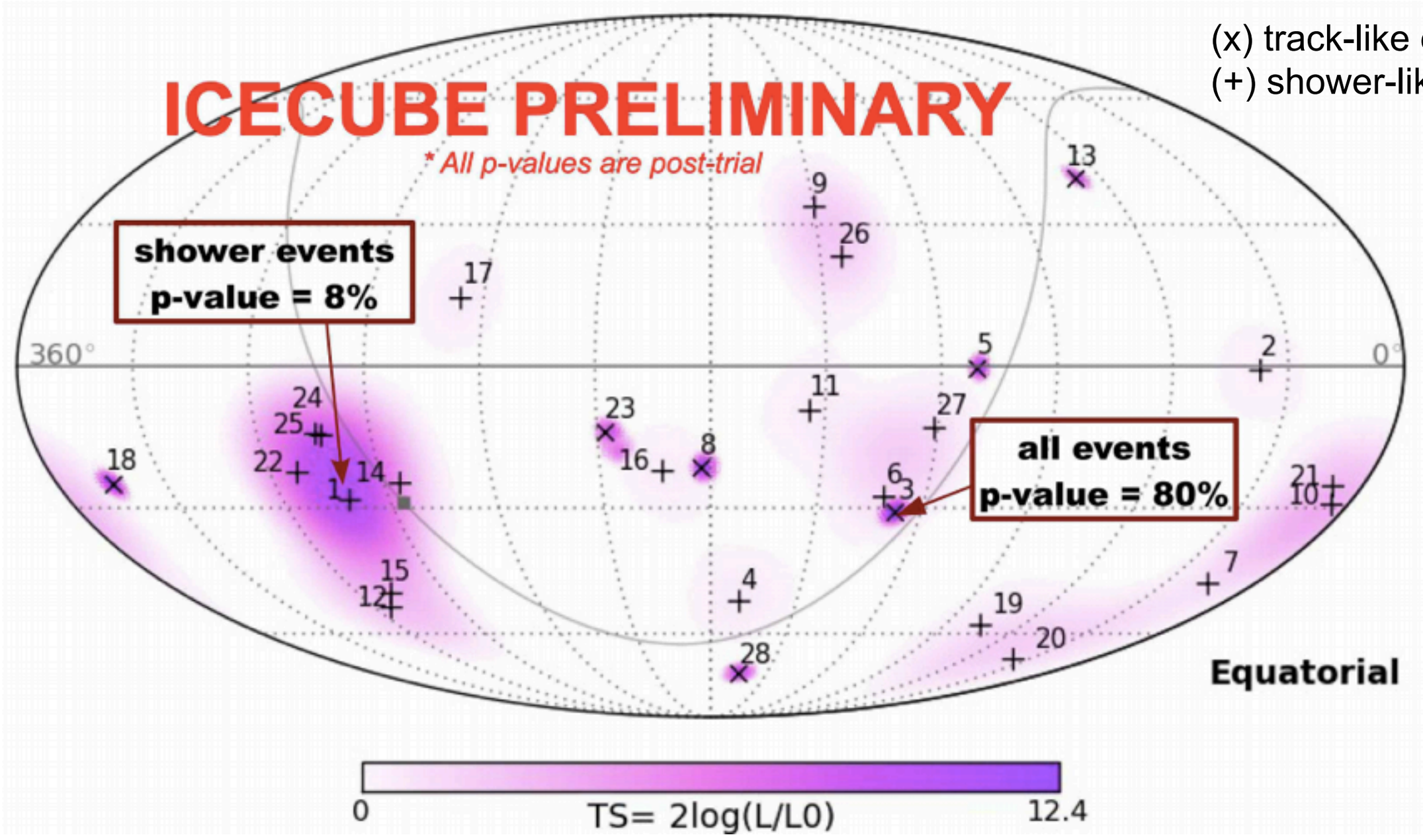
> **Spectrum** and **zenith distribution** compatible with an astrophysical flux with a power-law spectrum ($\Phi \sim E^{-2}$) between 60 TeV and 2 PeV.

Atmospheric neutrinos on southern hemisphere suppressed by “self-veto”:

- p + air → X + ν_μ + ν_e + ... + μ
- high-energy μ from shower triggers veto



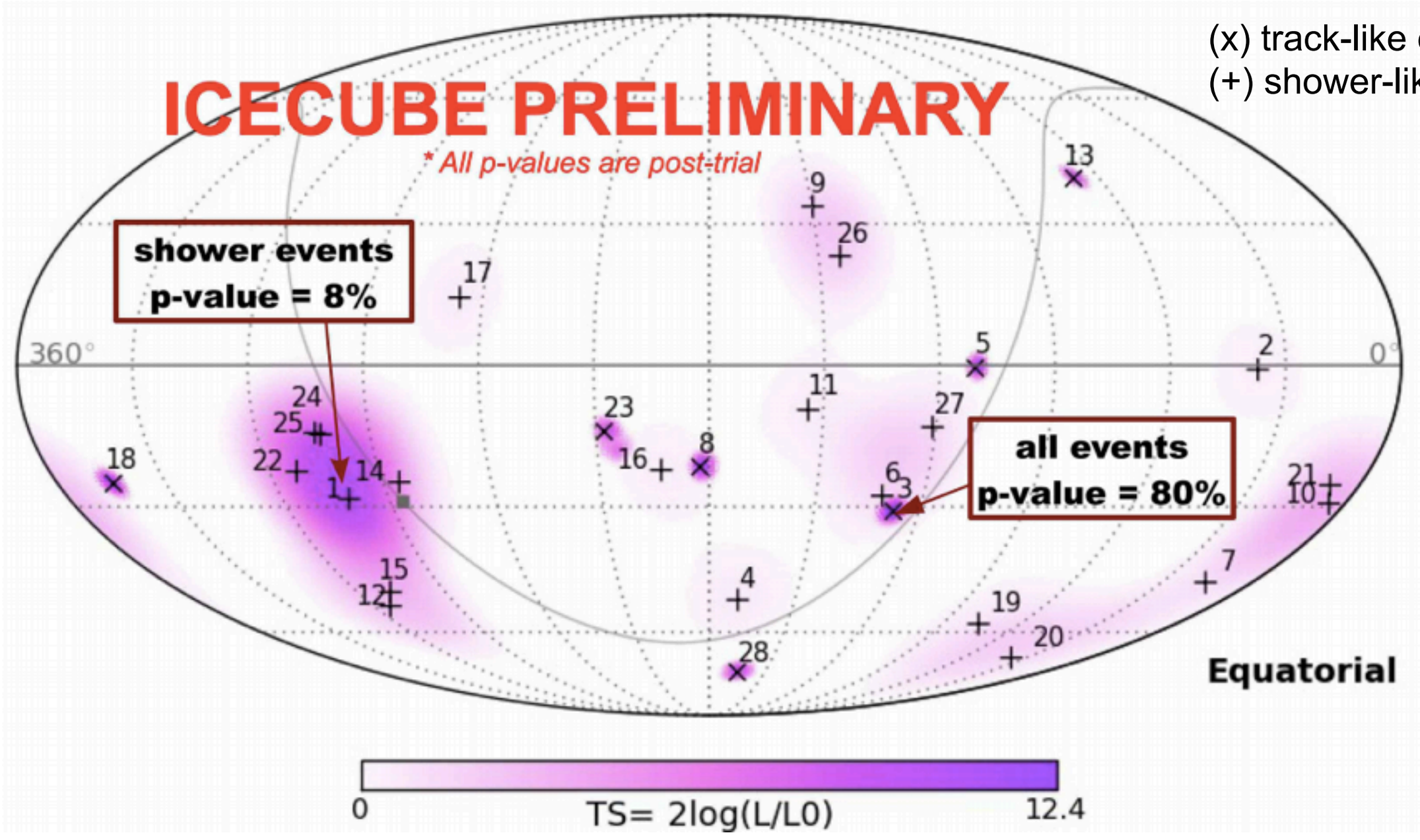
Distribution of high-energy neutrinos on the sky.



- **21 shower-like** events, 7 track-like events
- Dominance of shower-like events expected from astrophysical neutrinos due to flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

Distribution of high-energy neutrinos on the sky.

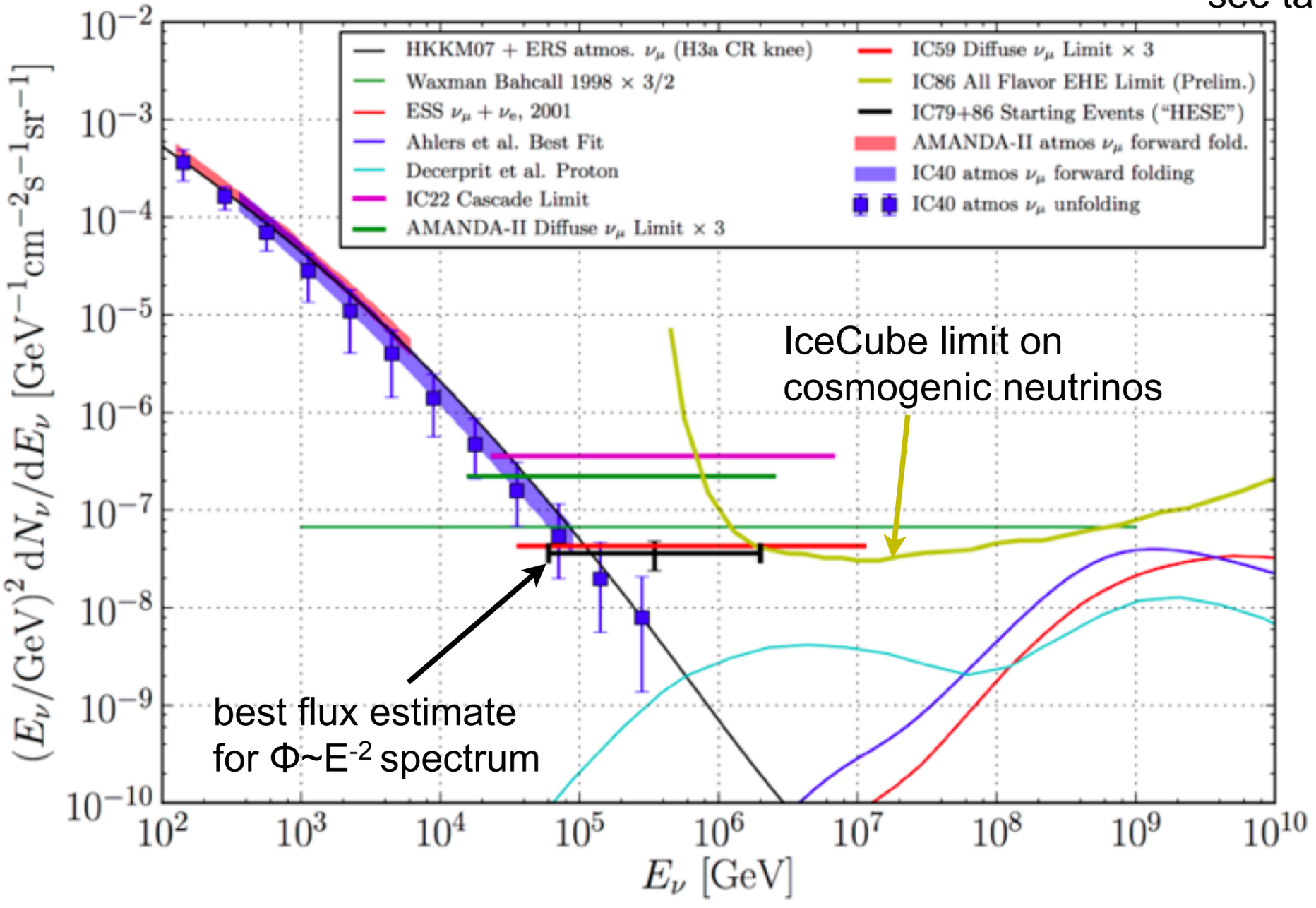
(x) track-like event
(+) shower-like event



- **Event distribution** compatible with expectations from background + isotropic astrophysical flux.
- **No significant correlation** in space/time with GRBs found.

Searches for diffuse astrophysical and cosmogenic neutrinos.

see talk by M. Ahlers



- Observed excess is **too low in energy** to be of **cosmogenic** origin.
- IceCube starts to probe the phase space of cosmogenic neutrino models.

A global spectral fit to all IceCube data.

see talk by L. Mohrmann

Hypothesis:

$\phi_{astro} \sim E^{-2} \cdot \exp(E/E_{cut})$

Goodness-of-fit:
7.8 %

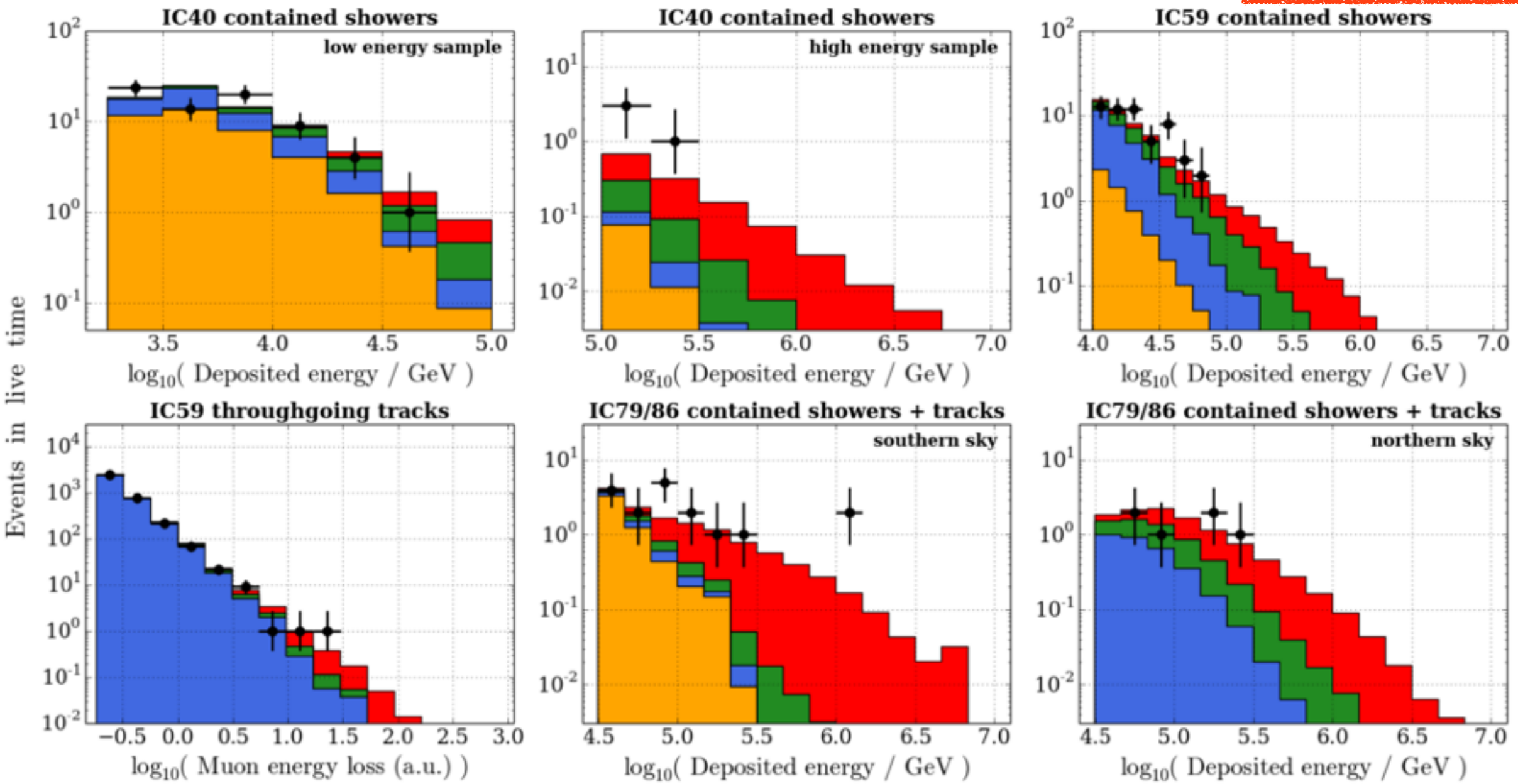
IceCube Preliminary

Atmospheric ν (conv.)
Atmospheric ν (prompt)
Atmospheric μ
Astrophysical ν
Data

$\phi_{prompt} = (2.8^{+2.0}_{-2.0}) \cdot$ [Enberg + Gaisser H3a]

$E^2 \phi_{astro} = (1.0^{+0.8}_{-0.5}) \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}

$E_{cut} = (1.8^{+5.0}_{-1.0})$ PeV



> **Hard spectrum** with cutoff: $\Phi \sim E^{-2} \exp(-E/E_{cut})$

A global spectral fit to all IceCube data.

see talk by L. Mohrmann

Hypothesis:

$\phi_{\text{astro}} \sim E^{-\gamma}$

Goodness-of-fit:

10.0 %

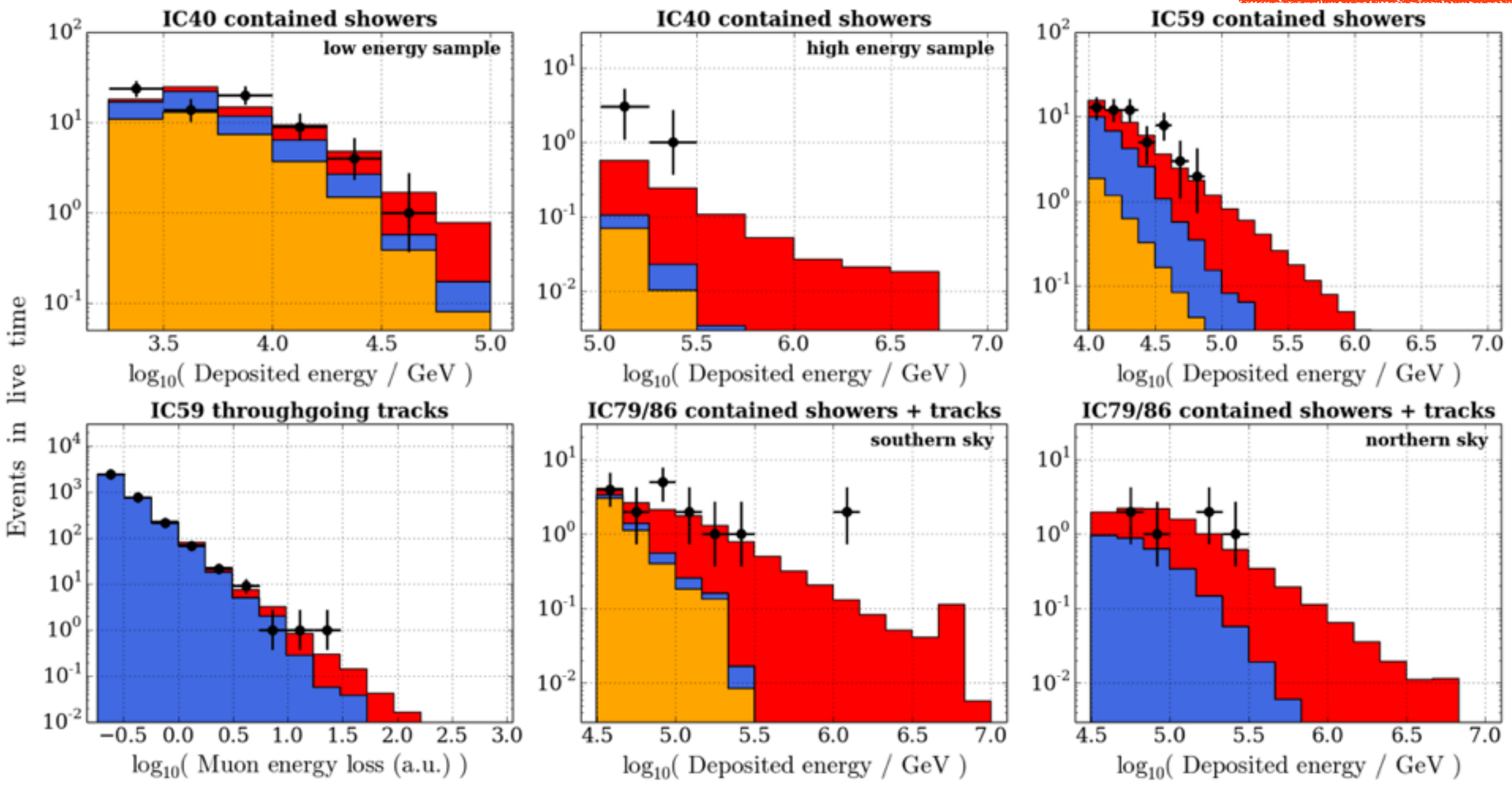
IceCube Preliminary

Atmospheric ν (conv.)
Atmospheric ν (prompt)
Atmospheric μ
Astrophysical ν
Data

$\phi_{\text{prompt}} = (0^{+1.6}_{-0.0}) \cdot$ [Enberg + Gaisser H3a]

$E^{2.7}\,\phi_{\text{astro}} = (6.8^{+1.8}_{-1.8}) \cdot 10^{-5}\,\text{GeV}^{1.7}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{cm}^{-2}$

$\gamma_{\text{astro}} = (2.7^{+0.2}_{-0.2})$



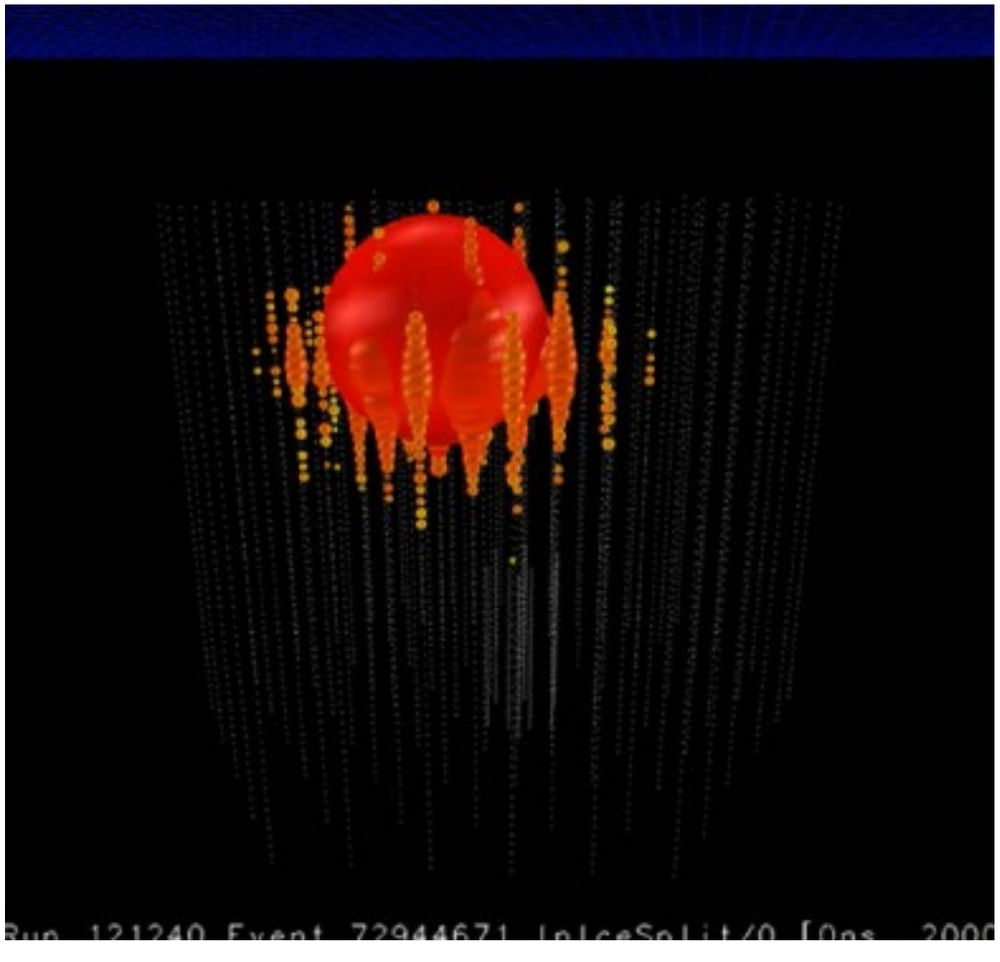
> **Pure power-law** with unknown index: $\Phi \sim E^{-\gamma}$

More results expected soon.

- Analysis of **2012/2013** IceCube **data** (run period from May 2012 - Apr 2013).

- **Better constraints** on atmospheric neutrino fluxes from **low-energy** contained/semi-contained events.

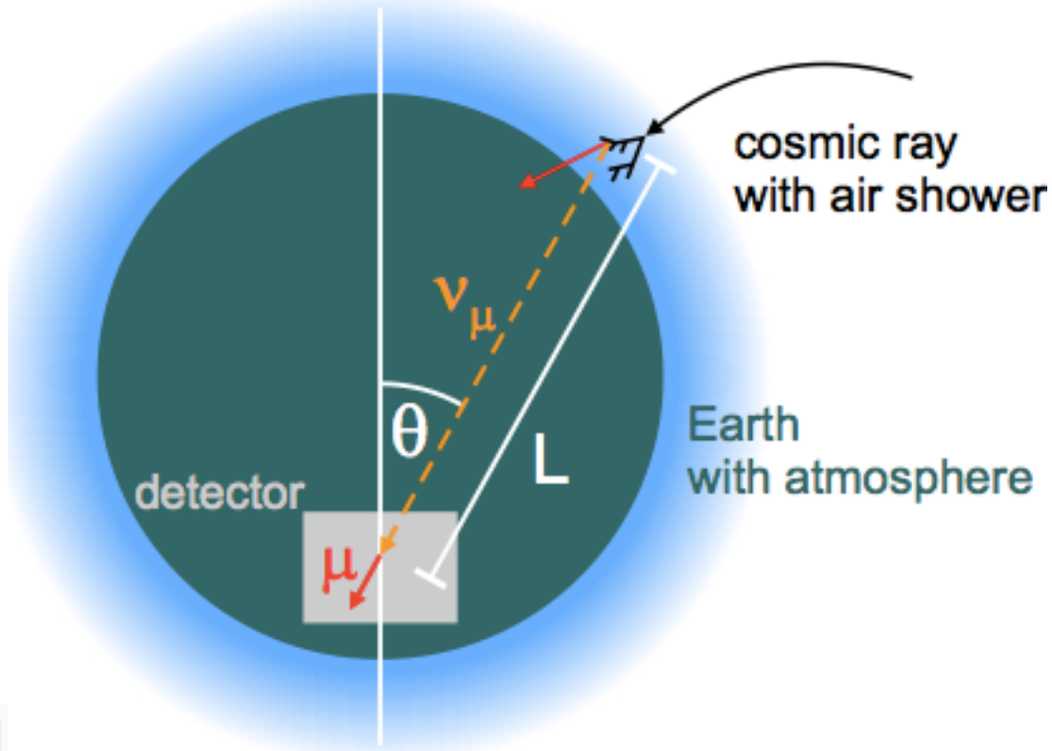
- Search for **excess events** in the **dE/dx spectrum** of through-going tracks with the completed IceCube observatory.

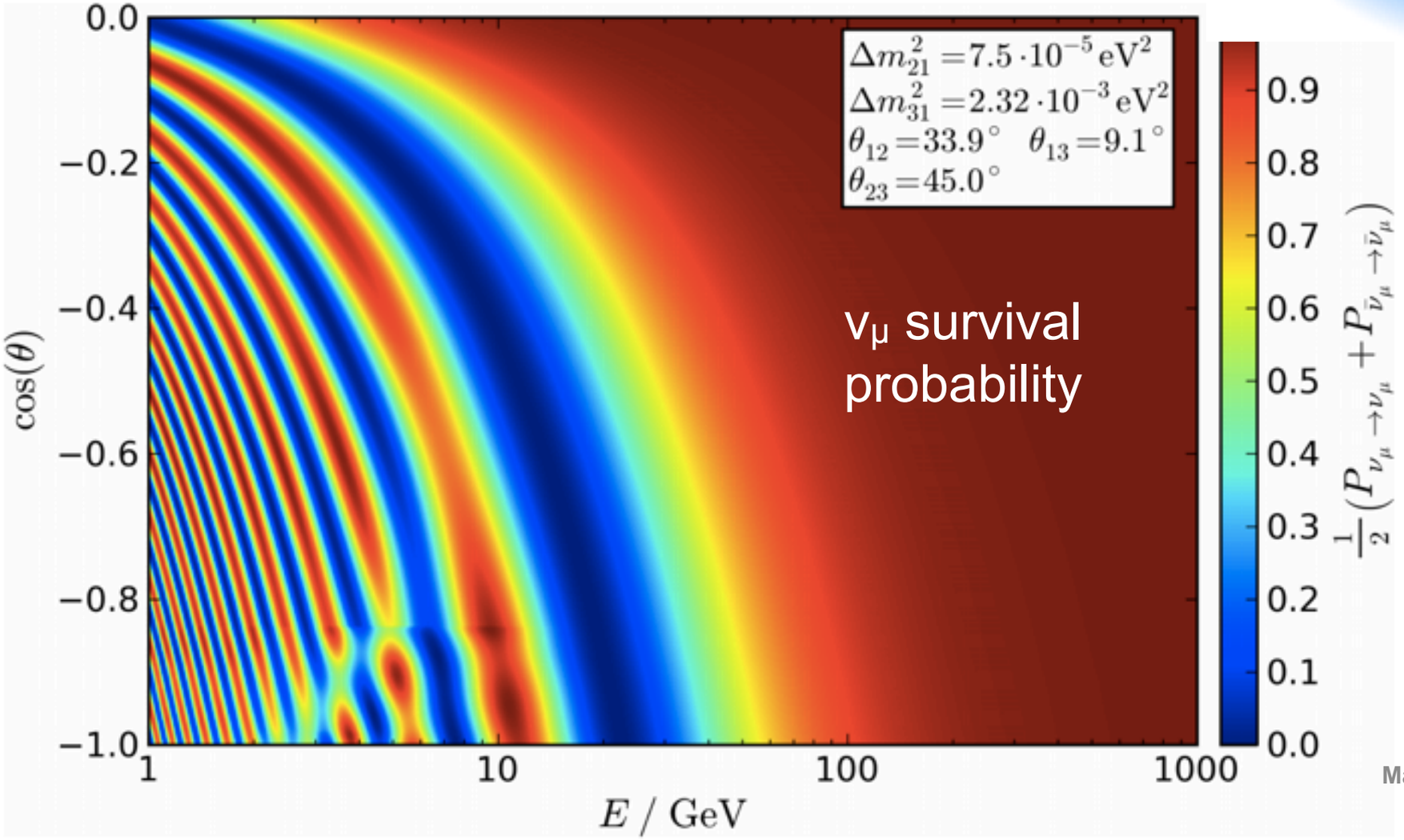


Another PeV-class neutrino in pre-scaled 2012/2013 data sample used for analysis development (10% of available data).

Studies of neutrino properties with IceCube.

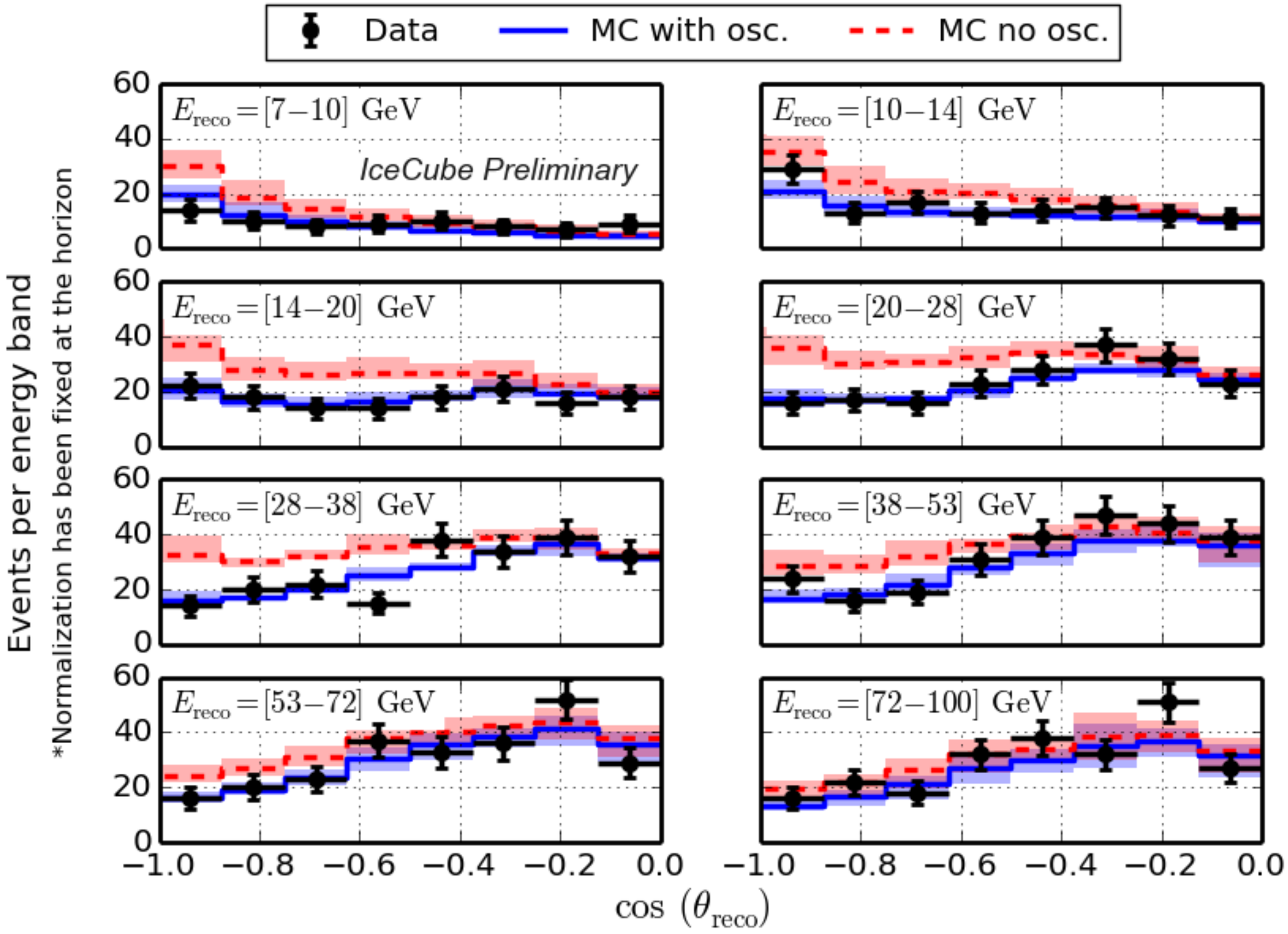
- Measurement of Δm^2_{23} and $\sin^2(2\theta_{23})$ using **DeepCore** sub-detector.
- **Zenith angle** of atmospheric neutrinos reflects different **baselines L**.
- For vertical events: ν_μ **survival probability** minimum **~ 25 GeV**.





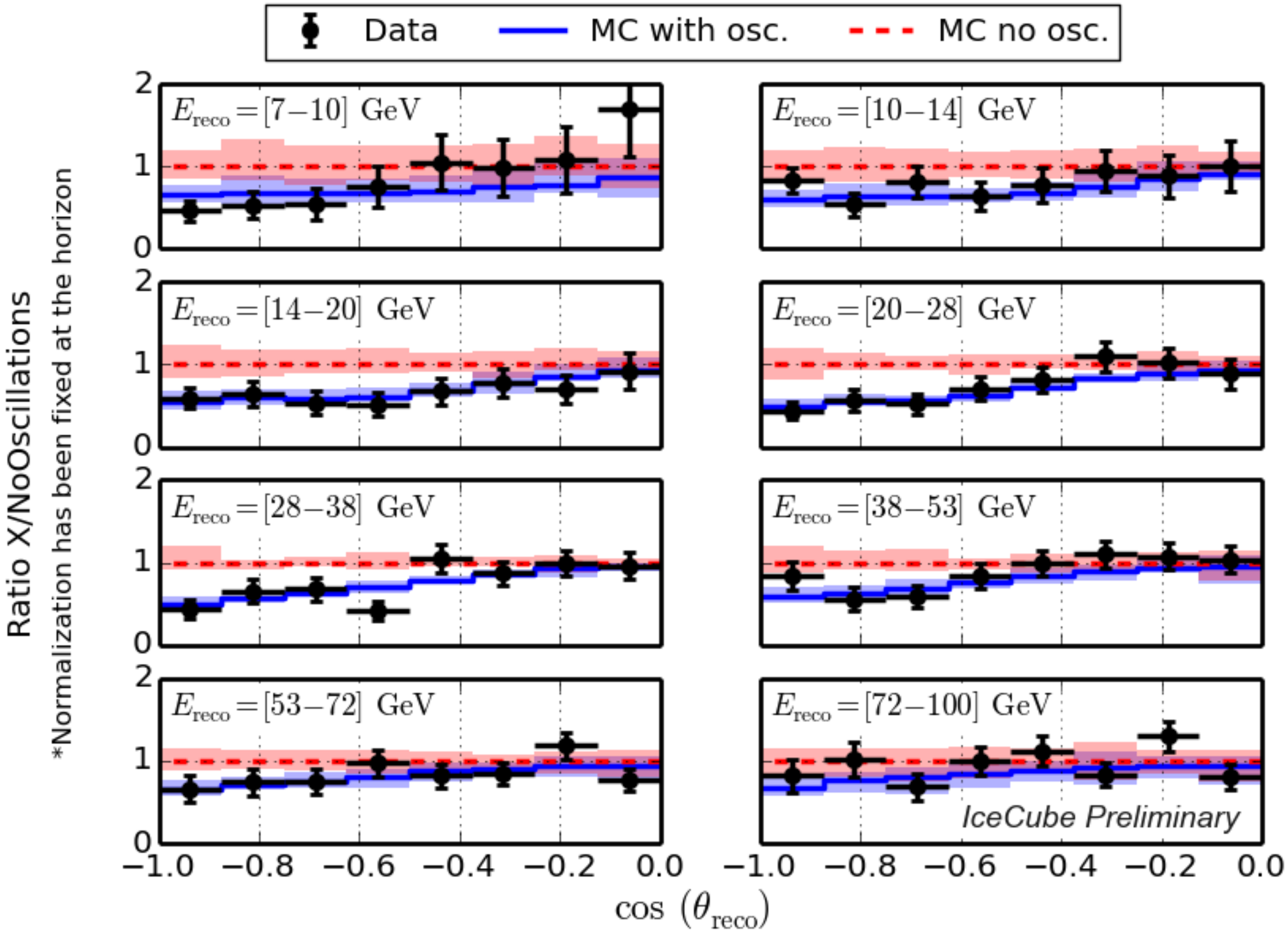
- High-energy events can be used to **control systematics**.

Studies of neutrino properties with IceCube.



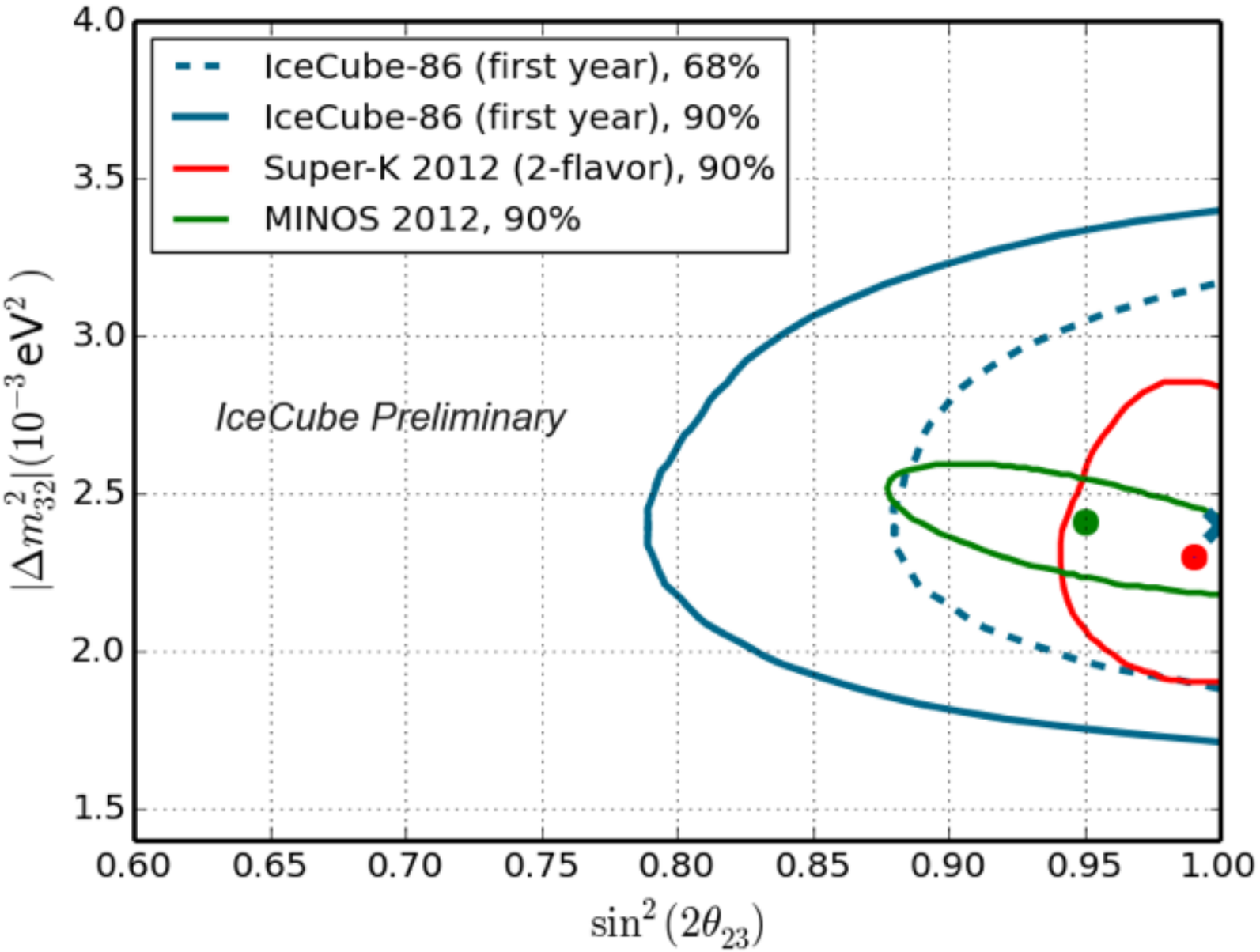
> Analysis performed using **one year** of available full **IceCube** data.

Studies of neutrino properties with IceCube.



> Analysis performed using **one year** of available full **IceCube** data.

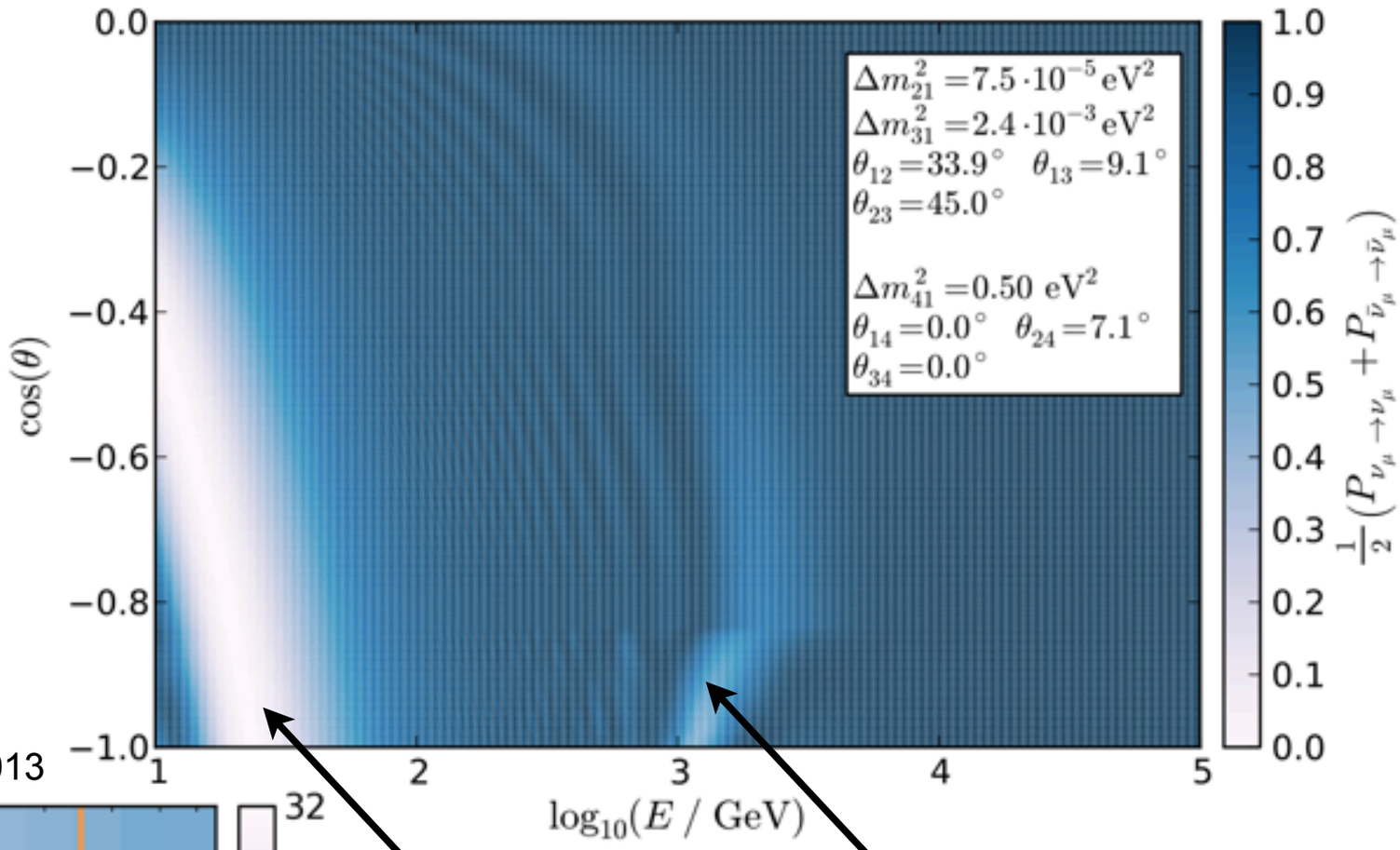
Constraints on oscillation parameters.



- **Promising constraints** on oscillation parameters from analysis.
- Uncertainty band **dominated by statistics** → Competitive constraints from multi-year dataset.

Sensitivity to sterile neutrinos.

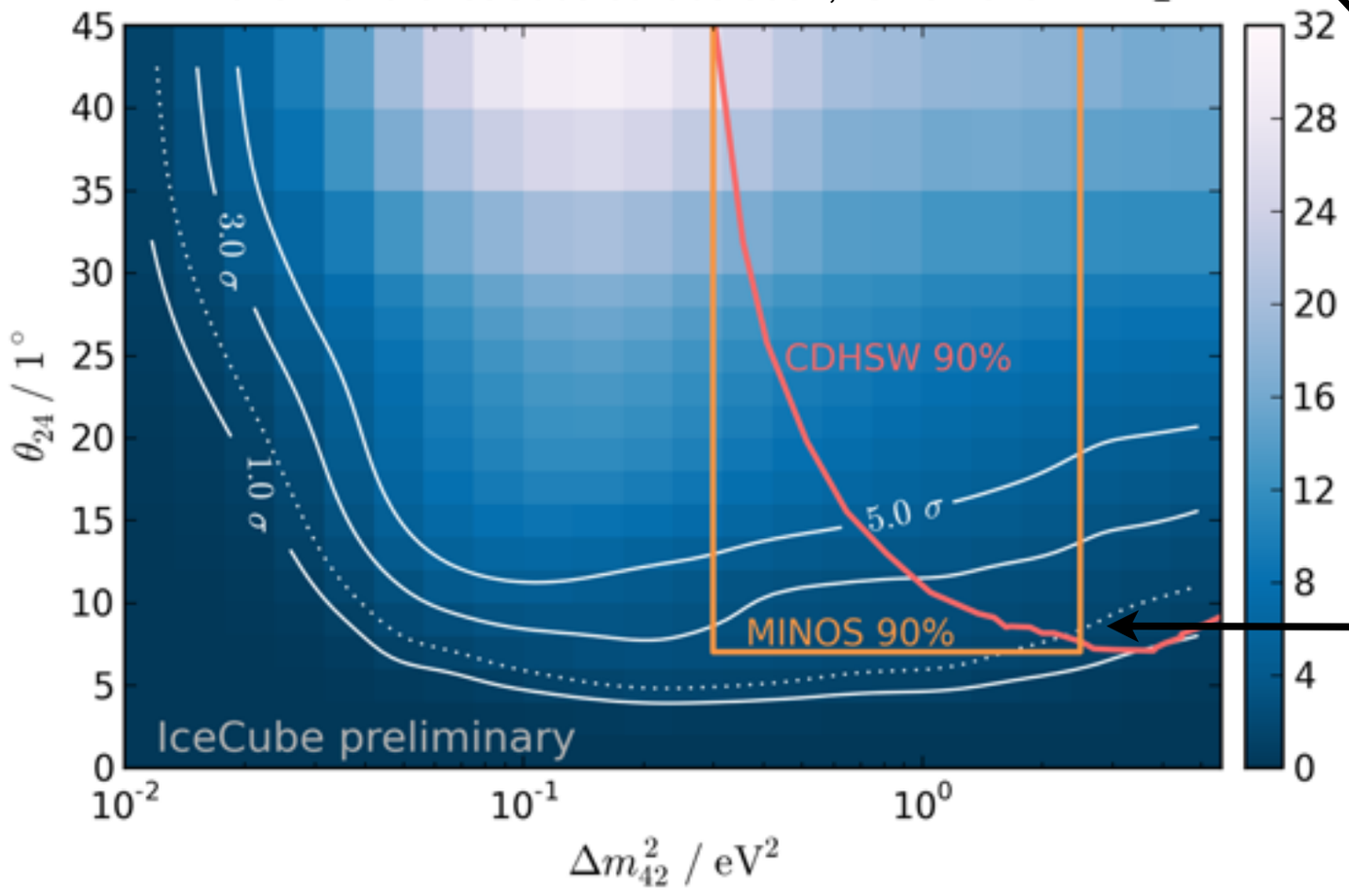
- IceCube is sensitive to **O(eV) sterile neutrinos.**
- Search for **oscillation** patterns of **TeV neutrinos.**
- **Competitive limits** expected from full IceCube array.



Standard oscillations

Sterile neutrino oscillations

M. Walraff for the IceCube collaboration, ICRC 2013



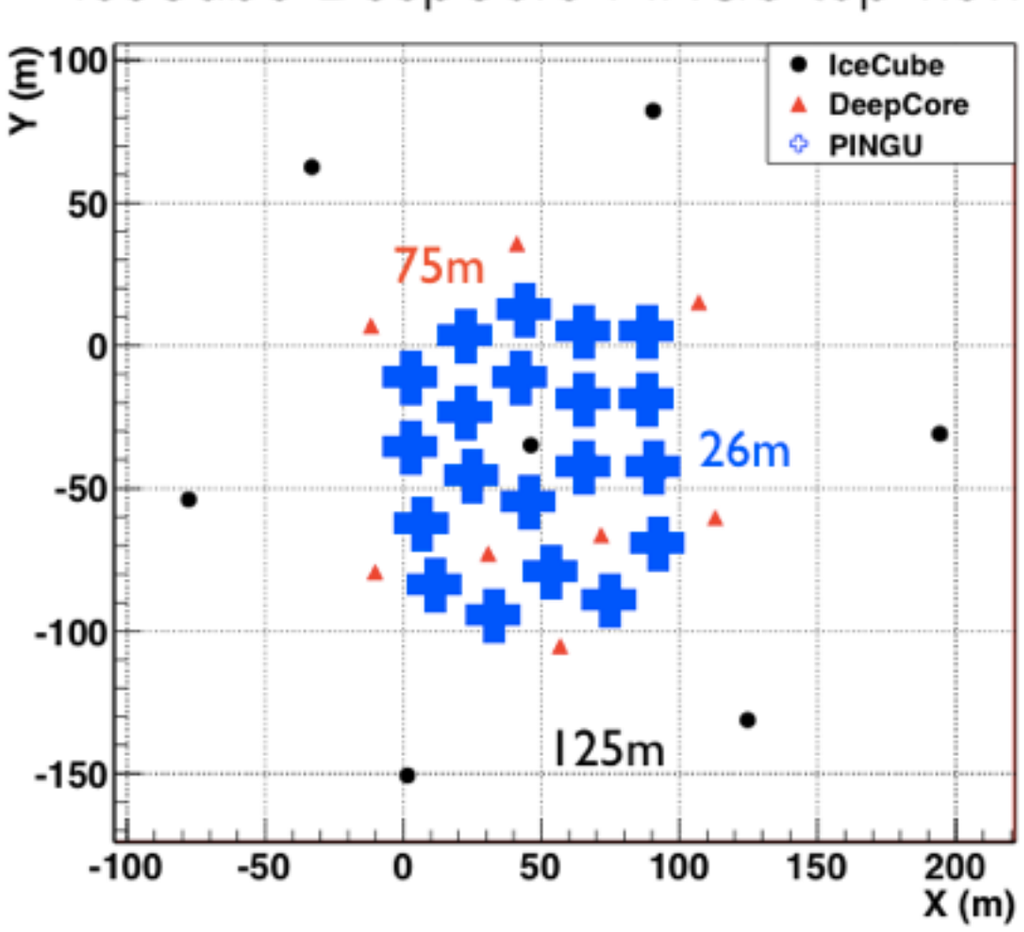
IceCube 5-year 90% exclusion sensitivity

Beyond IceCube.

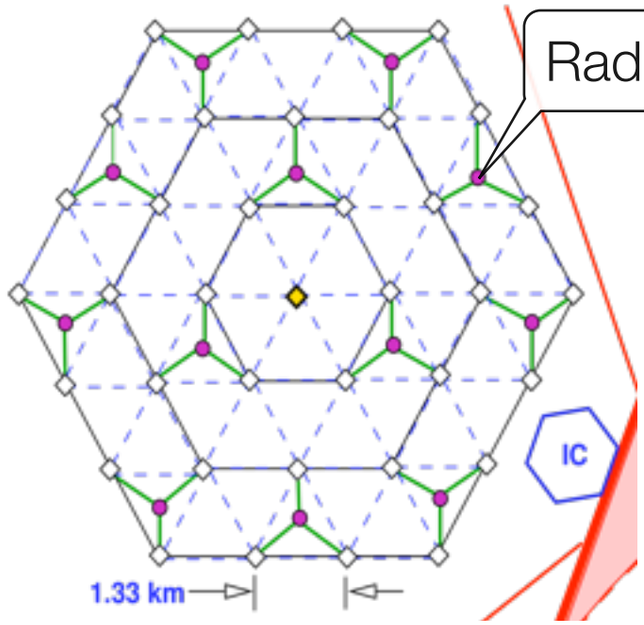
Increase of core density

PINGU

- **20-40 new strings** inside the DeepCore volume.
- **Energy threshold** reduced to **1 GeV.**
- Focus on measurement of **neutrino mass hierarchy.**

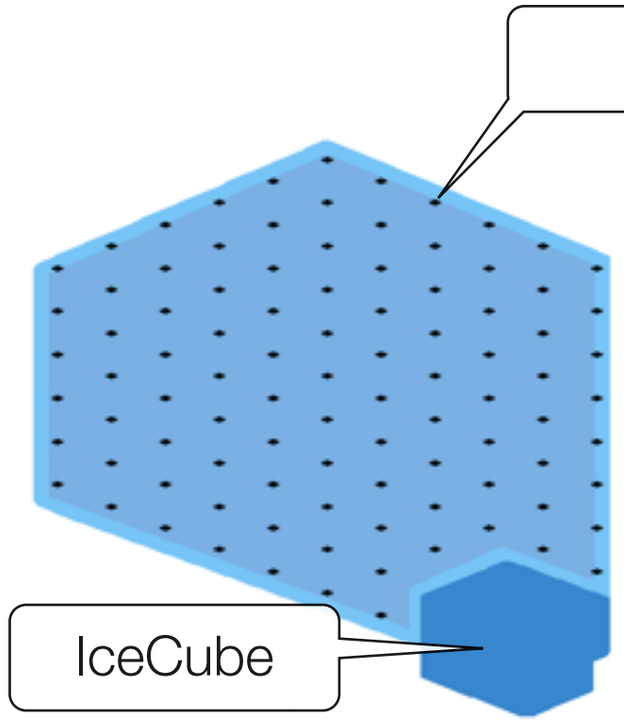


Extensions to larger volumes



Askarian Radio Array (ARA)

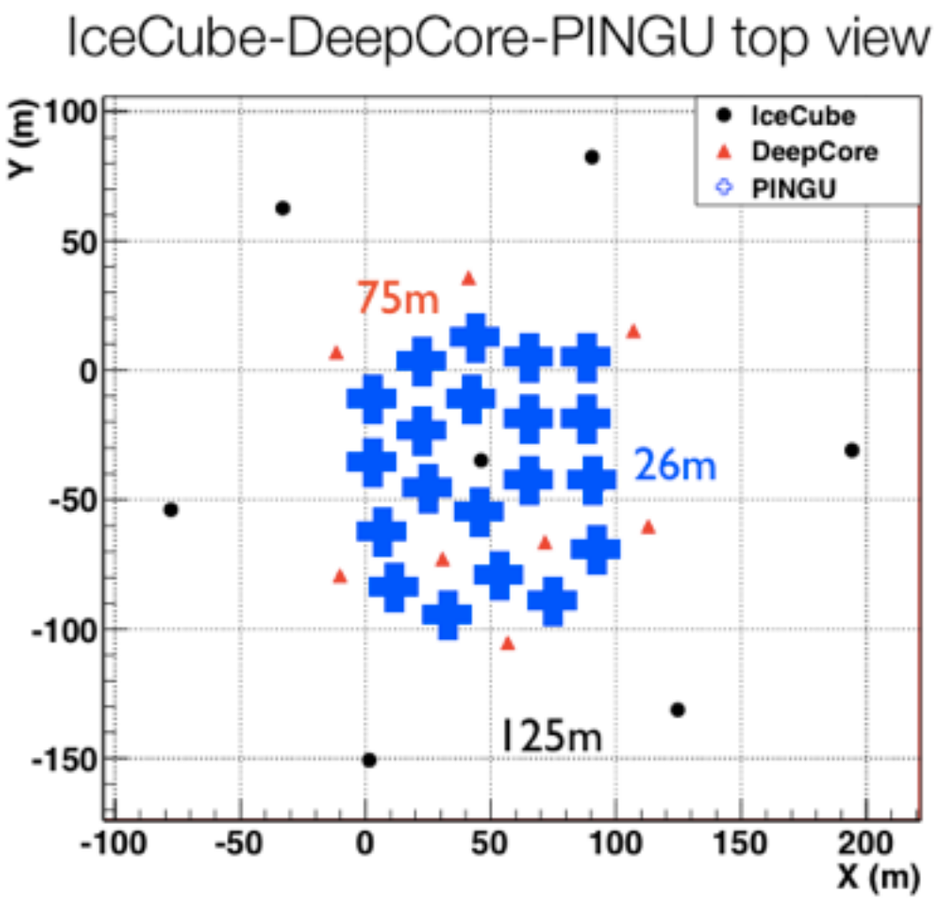
- InIce Radio array for **>30 PeV** neutrinos
- several **tens of km²** surface area

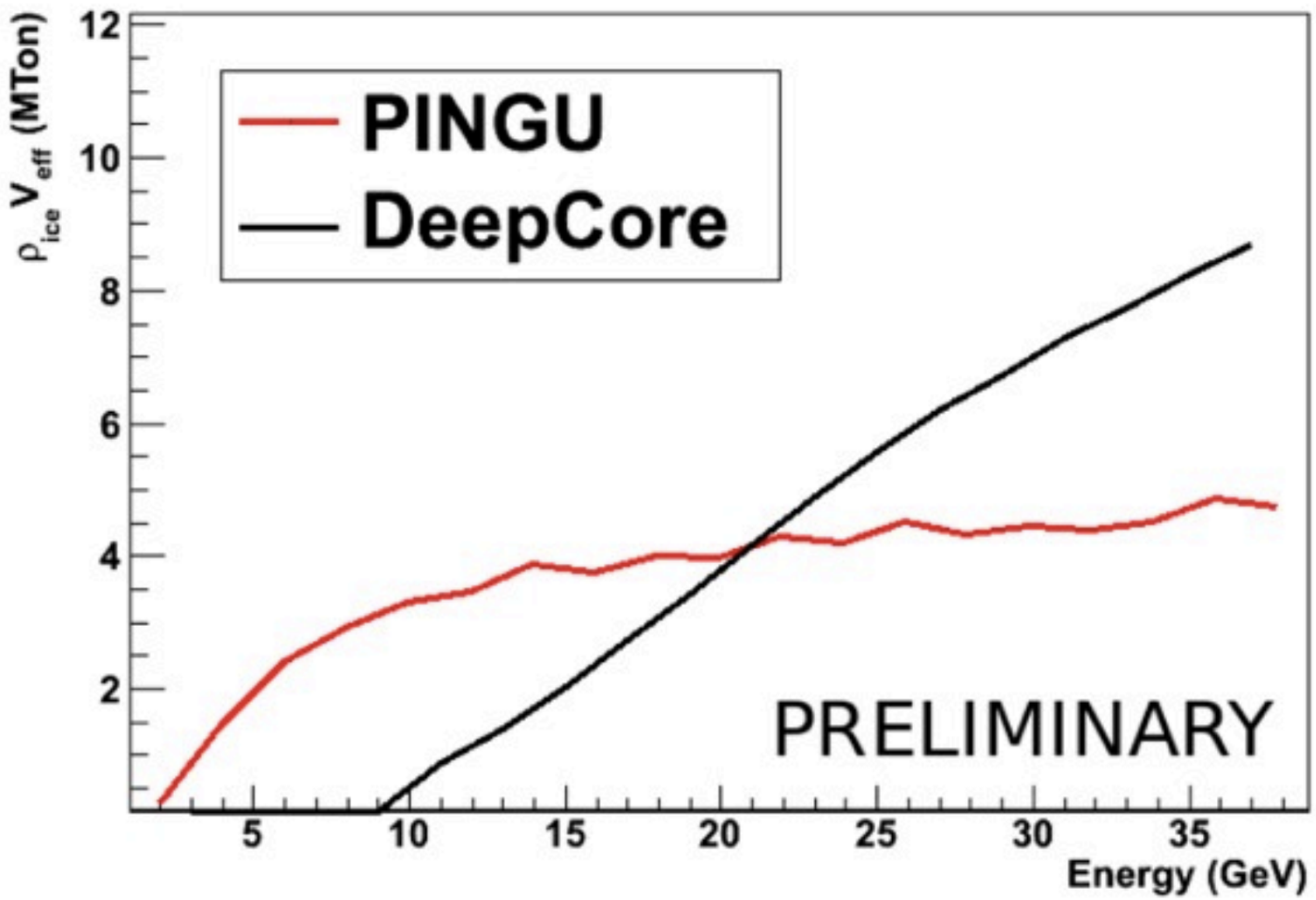


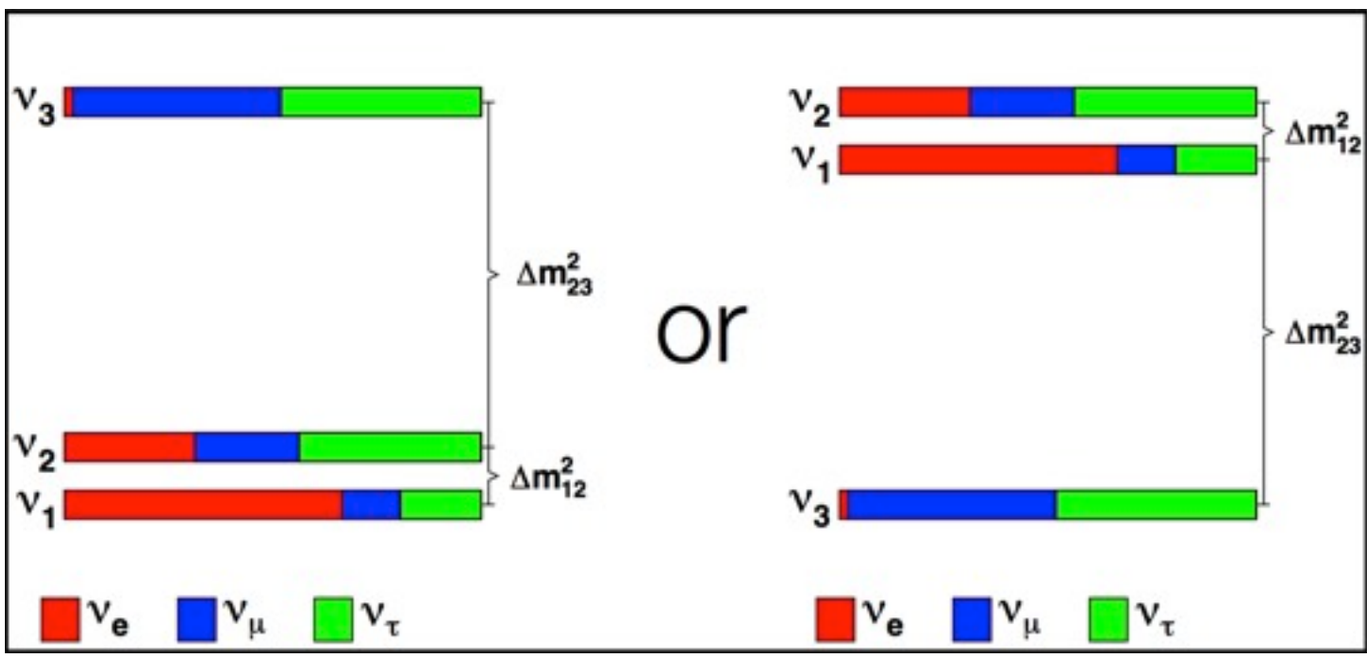
IceCube ++

- IceCube extension with **larger string spacing**
- Large **increase in effective area** above 10 TeV

Measurement of neutrino mass hierarchy with PINGU.



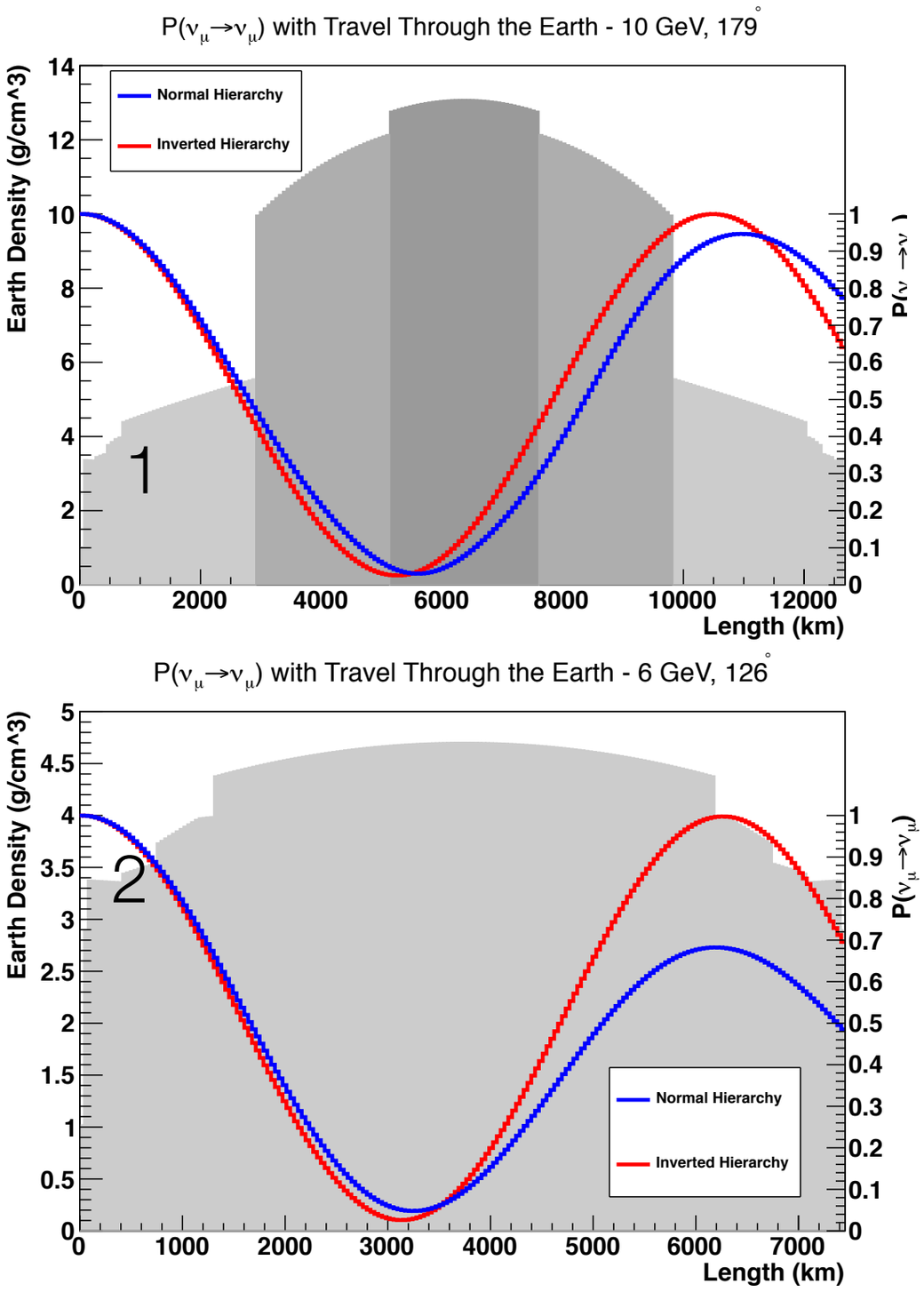


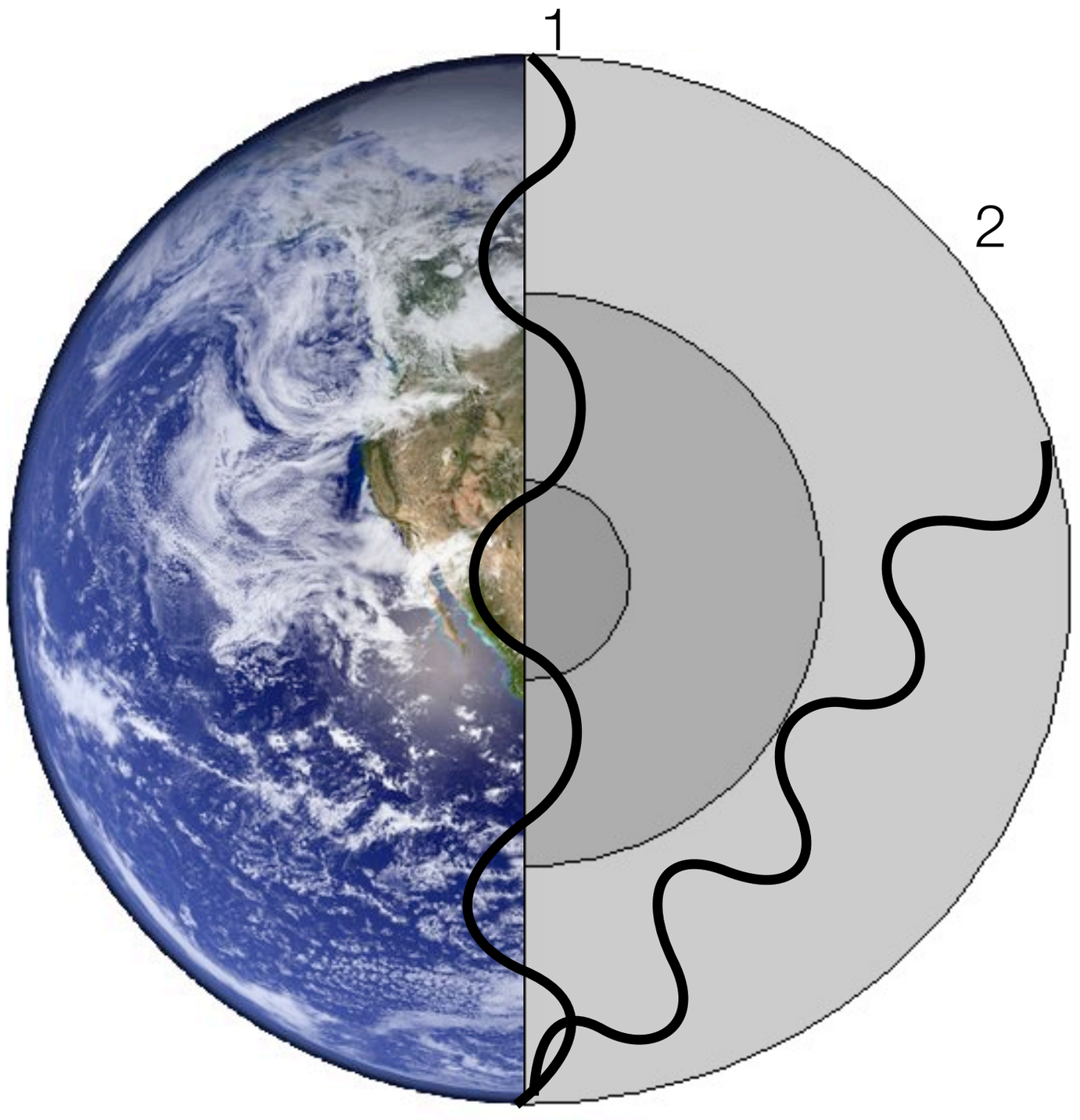


- **Mass hierarchy** is one of the last unknown fundamental properties of the neutrino sector.
- PINGU attempts to determine the hierarchy by providing a **megaton detector** for atm-ν with **1GeV threshold**.

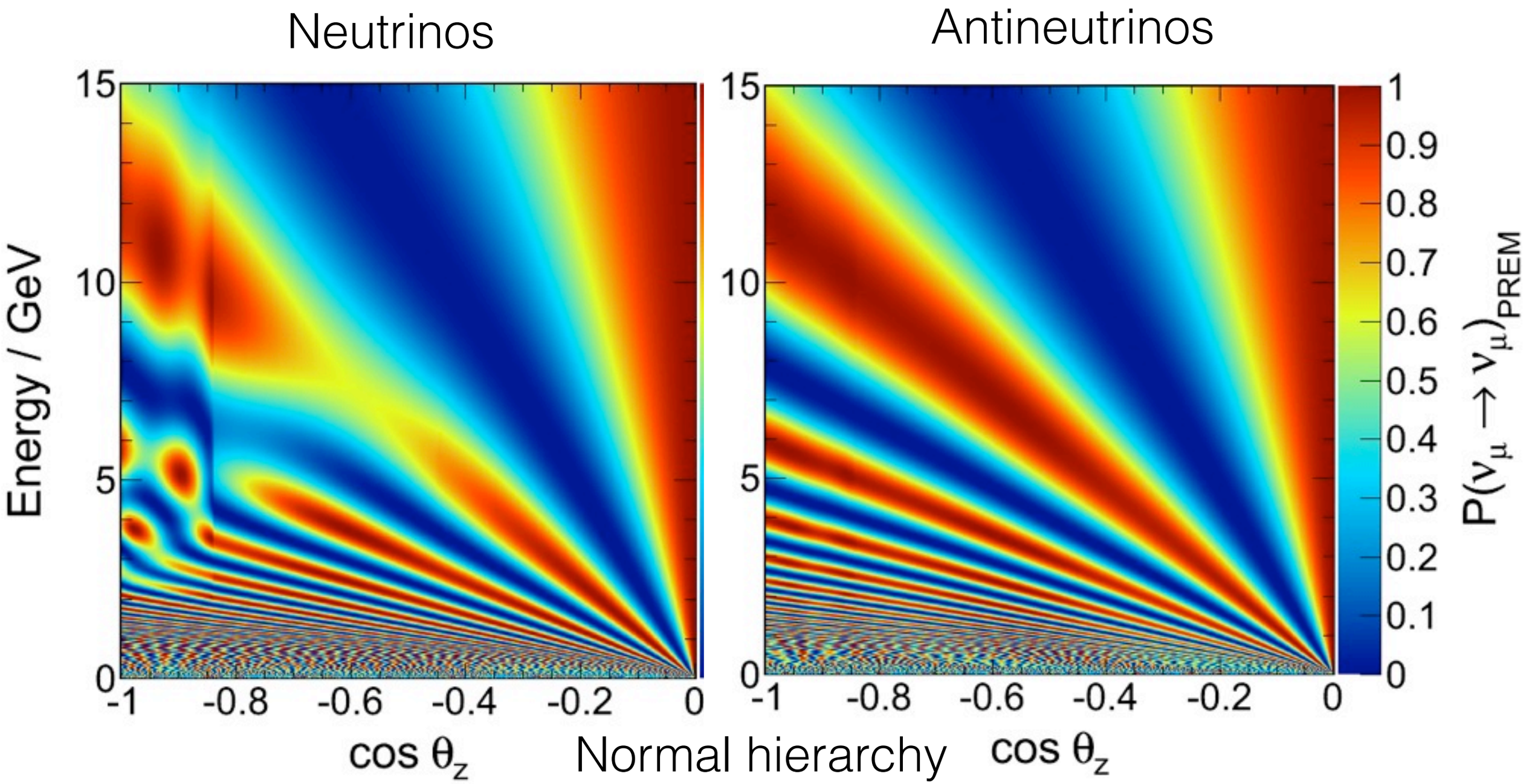
Measurement of neutrino mass hierarchy with PINGU.

- **Up to 20% differences** in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy



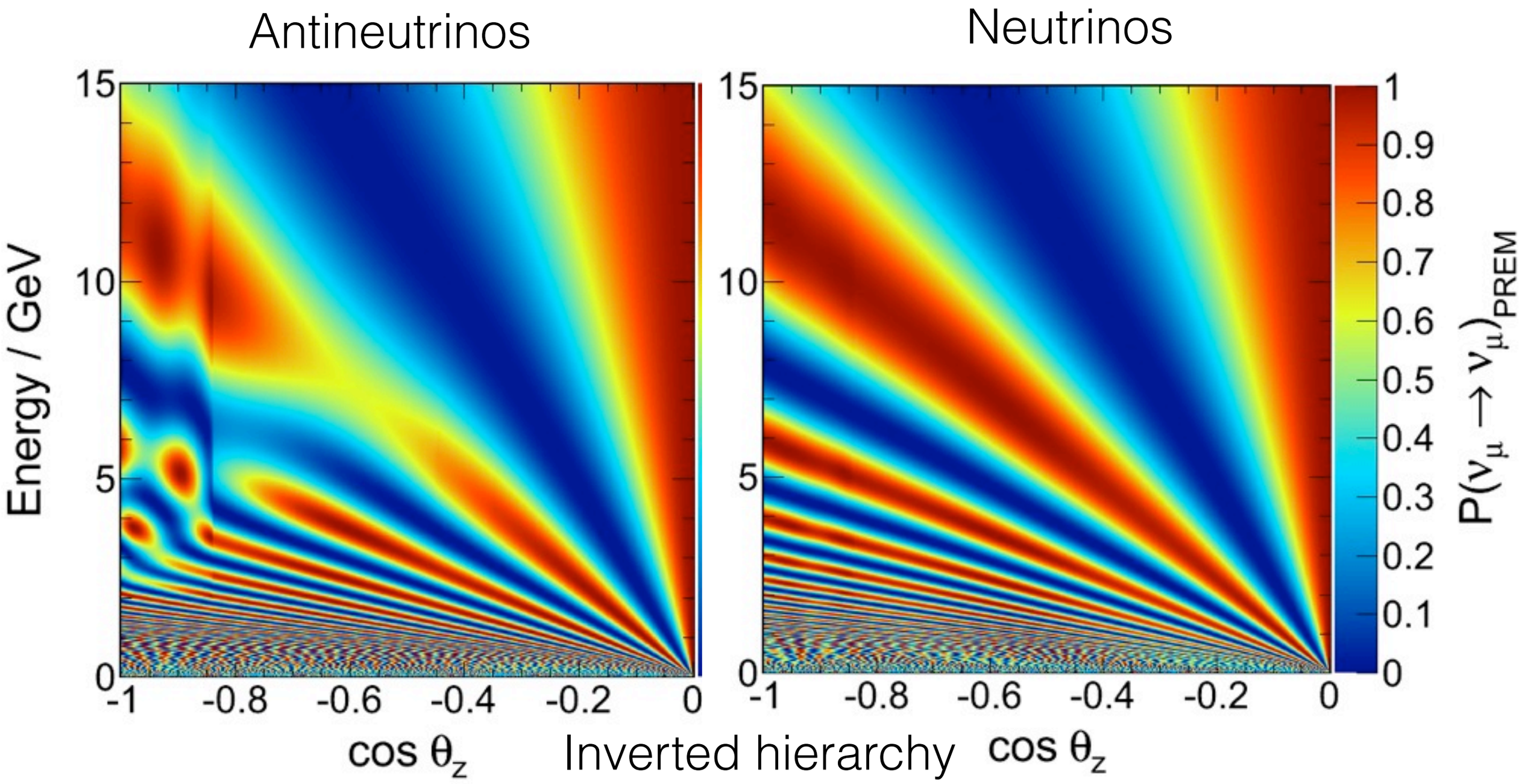


Muon neutrino survival probabilities for normal hierarchy.



> Survival properties for neutrinos and anti-neutrinos.

Muon neutrino survival probabilities for inverted hierarchy.



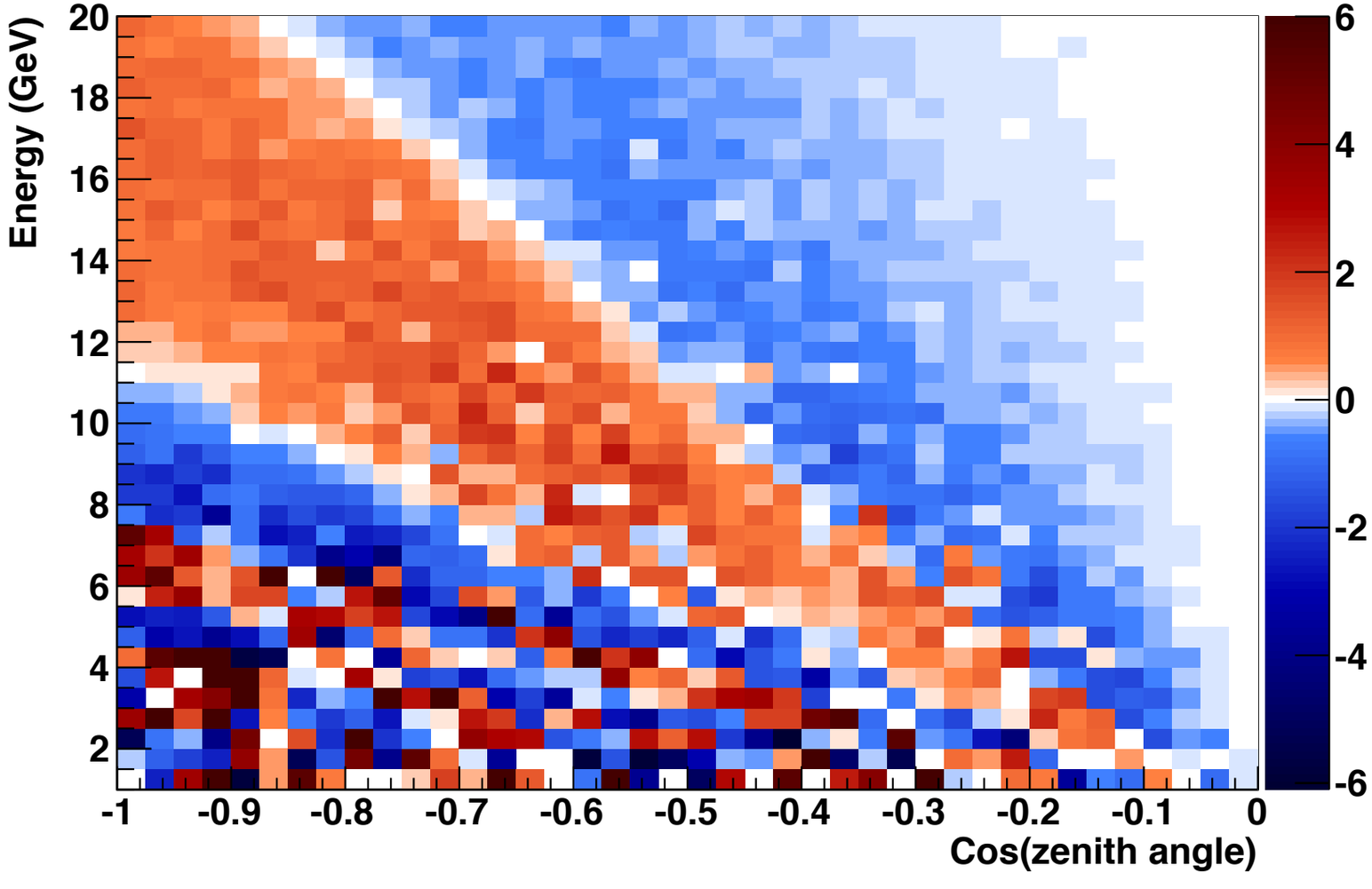
- **Survival probabilities switched** for neutrinos/anti-neutrinos in inverted hierarchy
- **PINGU cannot distinguish** neutrinos from anti-neutrinos ....
- ...but **rates** are **not the same**.

Measurement of mass hierarchy with PINGU.

- Need to measure **complicated pattern** in 2-dim distribution (E, cos(zenith))
- Good way to **visualize signature** of mass hierarchy:
  - **Distinguishability metric** (Akhmedov, Razzaque & Smirnov (arXiv:1205.7071)):

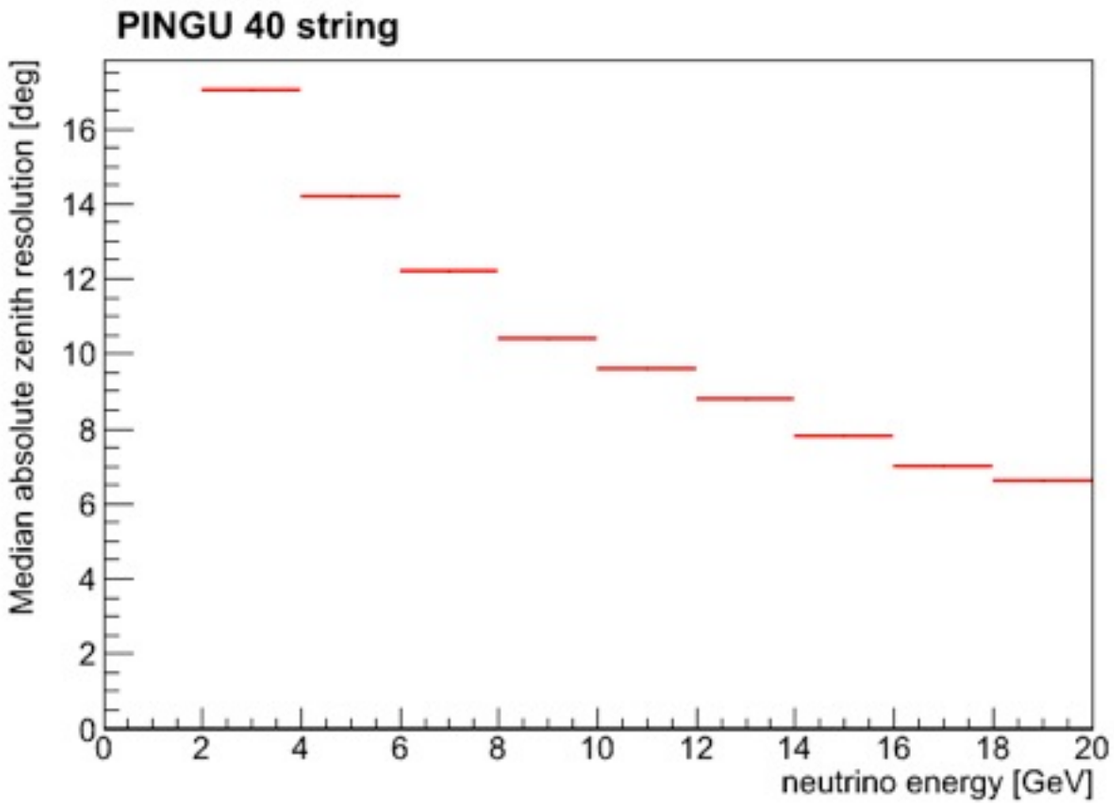
$$\frac{N_{obs,IH} - N_{obs,NH}}{\sqrt{N_{obs,NH}}}$$

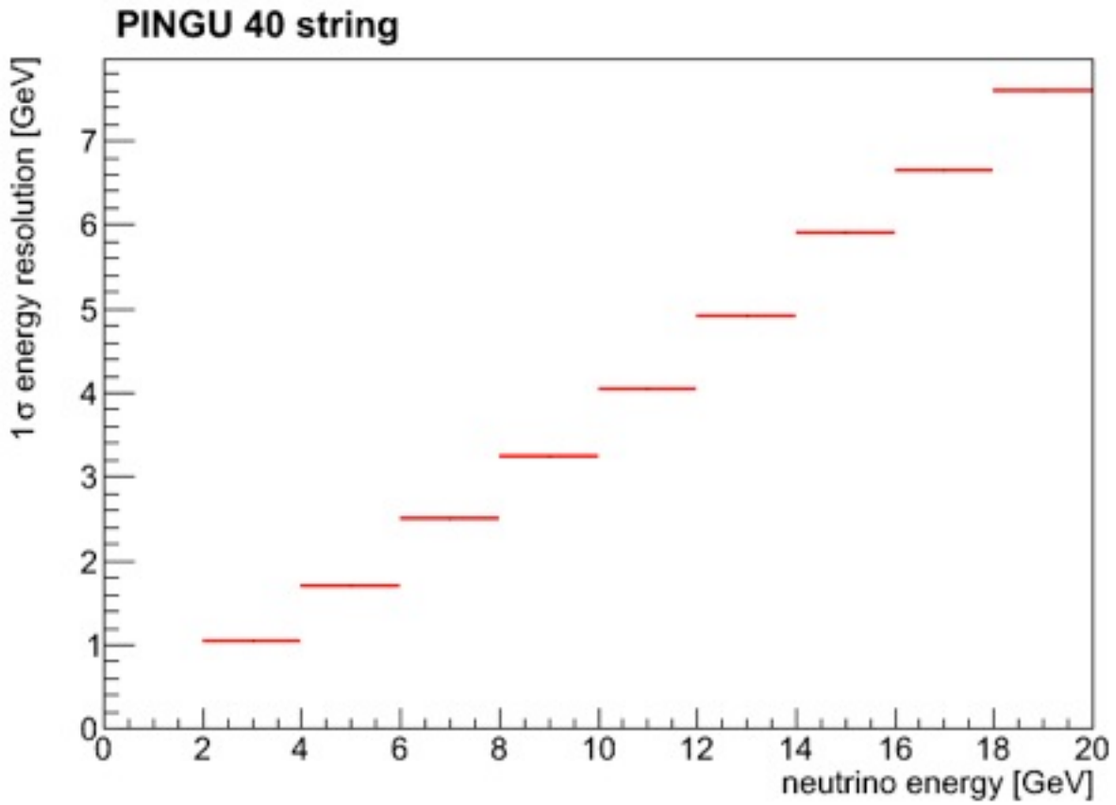
Distinguishability Metric $[(IH-NH)/NH^{1/2}]$



- Expected signal from inverted hierarchy in a **perfect detector.**
- Real detector will have **finite energy and zenith resolution**.

Performance studies for PINGU.



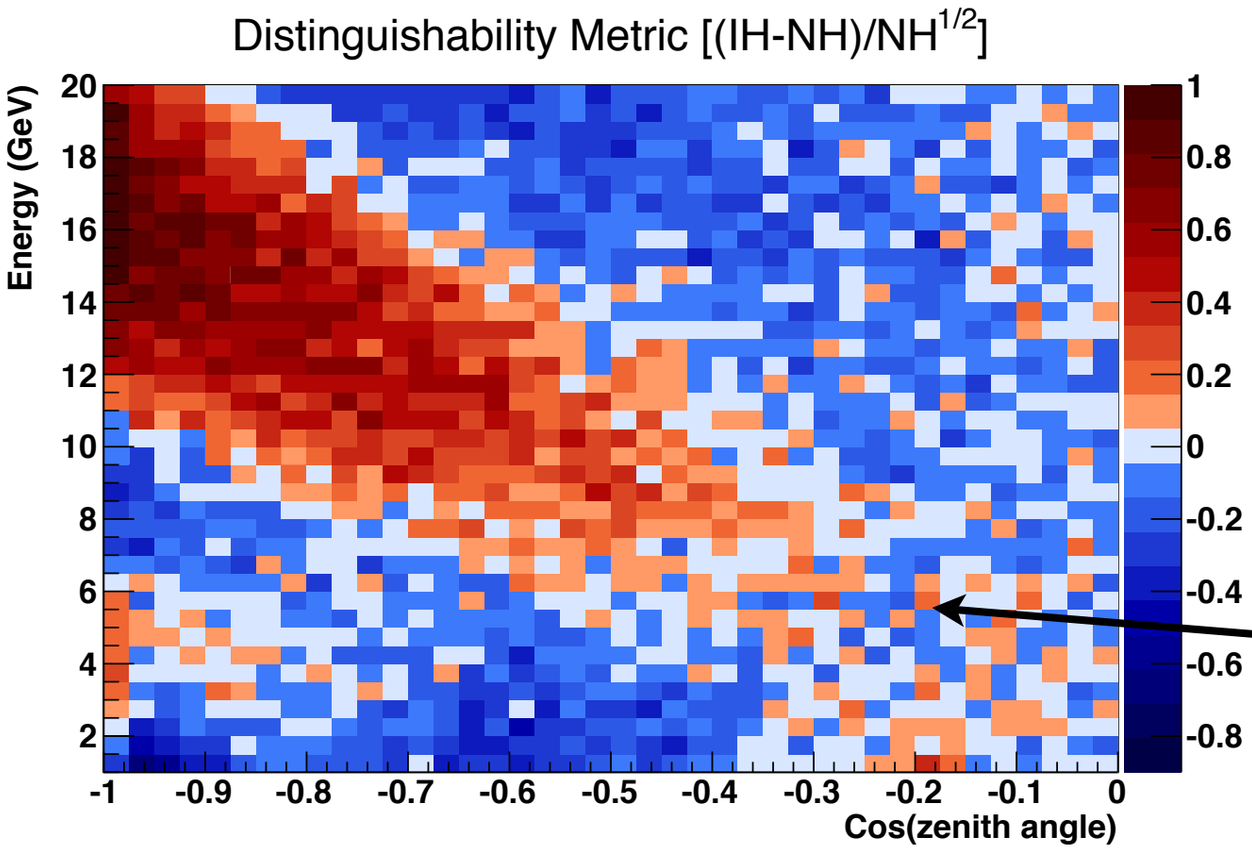


- Currently using **DeepCore algorithms** for reconstruction.

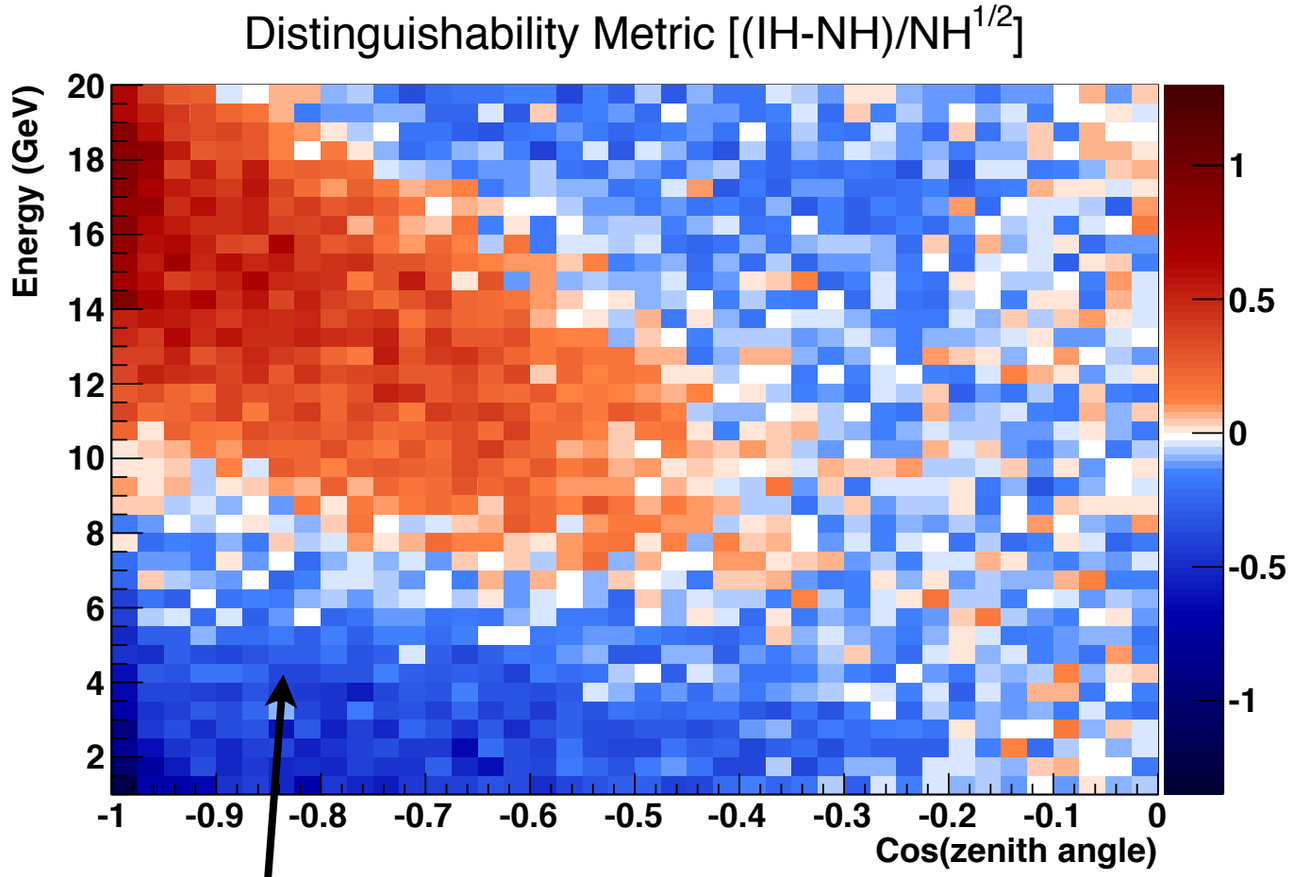
- **Systematics** studied so far:
  - θ_{23}, θ_{13}, Δm^2_{atm}, δ_{CP} within world average ±2σ ranges
  - Efficiency errors (30%)
  - Atmos. ν spectral index (±0.05)
  - Energy calibration (10% bias)
  - Pointing accuracy (10% bias)
  - Energy resolution (10% error)
  - Angular resolution (10% error)
  - Further studies underway now.

Measurement of mass hierarchy with PINGU.

- Good **identification of mass hierarchy** possible with realistic experimental resolution.



Zenith resolution: 10°
Energy resolution 1 GeV



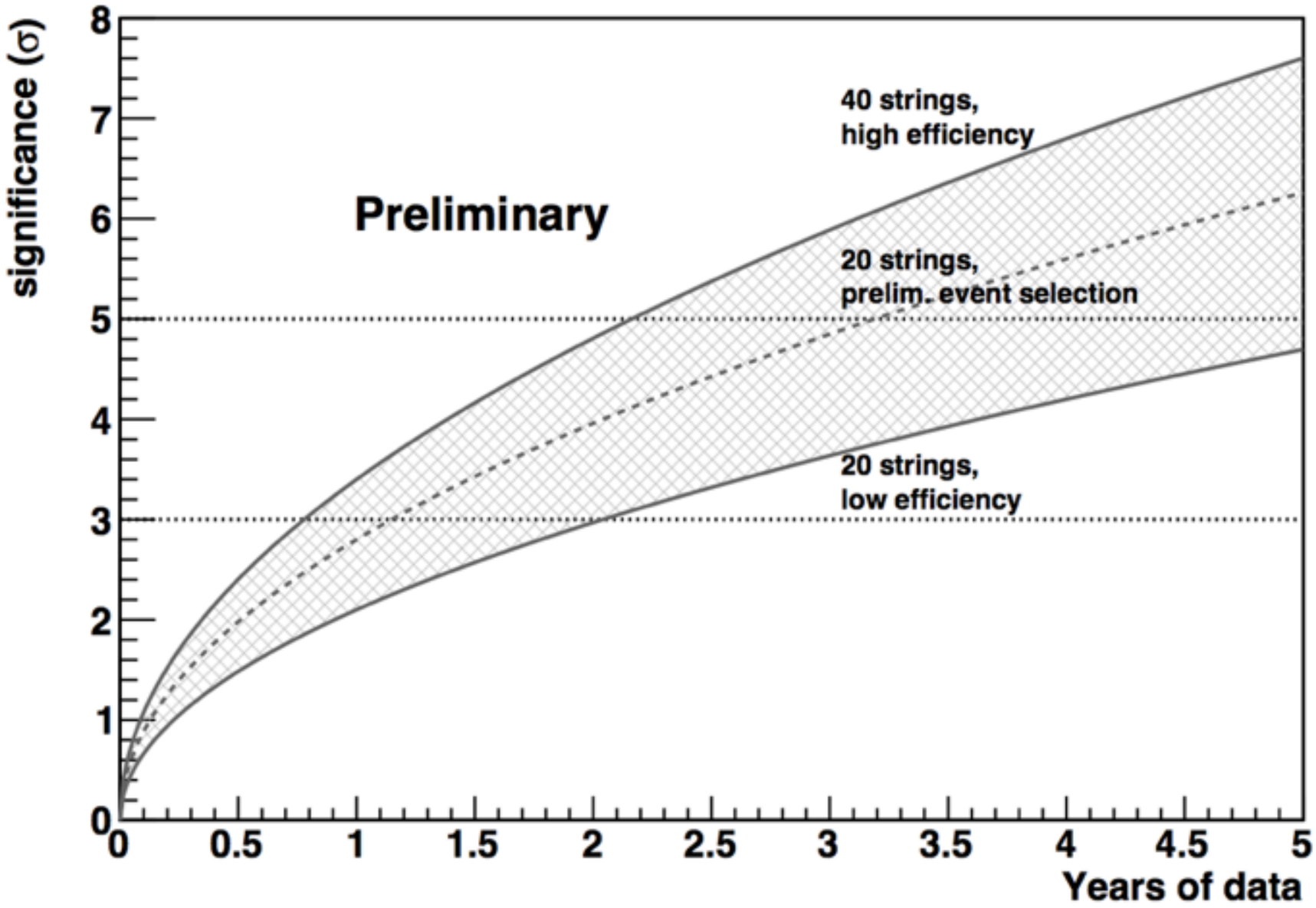
Zenith resolution: 12.5°
Energy resolution 3 GeV

conservative scenario

optimistic scenario

Mass hierarchy identification power.

> **Expected significance** from likelihood analysis of oscillation patterns.



Summary.

- IceCube is the first **gigaton scale** neutrino telescope in operation.

- Neutrino telescopes have **improved** the sensitivity for observations of astrophysical neutrinos by a **factor of 1000** in 13 years.

- So far **no discovery** of an individual neutrino source.

- IceCube observes the **first strong evidence** for **astrophysical neutrinos:**
  - Data incompatible with atmospheric expectations on the > 4σ level.
  - Compatible with a diffuse & isotropic astrophysical flux (no significant clustering observed).
  - Additional studies and data needed to constrain the spectral parameters of this flux.
  - Such studies are in an advanced stage with results expected soon.

- IceCube is a **unique infrastructure** to study **neutrino properties.**
  - Competitive studies of standard oscillation parameters with DeepCore.
  - Sensitivity to sterile neutrino oscillations with IceCube.
  - In the future: Mass hierarchy with PINGU.

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